Physical Modelling in Geotechnics

Development and challenges of physical modelling– Japanese contributions

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ABSTRACT: This lecture note describes development and challenges of physical modelling in geotechnical engineering with a special reference to Japanese contributions. A review on role of physical modeling is given. Development of modelling techniques and apparatus over a half century is presented in six selected areas, model preparation, soil characterization, modelling construction sequence, modelling earthquake, modelling ocean wave, and modelling tsunami events. A few scaling issues are discussed in relation to generalized scaling laws and spatial variability. Comments on large model test under 1 g environment are briefly given.

Keywords: model preparation, soil identification, construction sequence, earthquake, ocean wave, tsunami

1 INTRODUCTION

It is the highest honor for me, as the first Japanese student of Professor Andrew N. Schofield, to be able to deliver the 5th Schofield Lecture. I have chosen the topic "Development and Challenges of Physical Modelling" with a special reference to Japanese contributions.

When describing the historical development of centrifuge modelling as a major physical modelling, there are two questions to ask, "From which period should we begin?" and "Which aspect should we focus on?".

The first question is "From which period should we begin?" Craig (1995) wrote a comprehensive overview of geotechnical centrifuges, covering past, present as well as future perspectives. He begun the overview by the idea of Edouard Phillips with an initial field application to structural engineering in 1869, followed by the early works in the USA and the USSR in 1930s, including the paper by Pokrovskii and Fiodorov presented at the first International Conference on Soil Mechanics and Foundation Engineering (ICSMFE) in 1936. Pioneers of centrifuge modelling were well documented by Craig (2014), and Craig et al. (2015).

Considering the development over half a century, I would like to begin my note from 1969 at the 7th ICSMFE, when there were three papers related to centrifuge modelling submitted from the UK, Japan, and the USSR. Among the authors of the three papers, I would like to emphasize the great contributions of Professor Masato Mikasa, Osaka City University in Japan, and Professor Andrew N. Schofield, University of Cambridge in the UK. These two distinguished leaders can well be considered a headstream of modern geotechnical centrifuge modelling, one is in Asia and the other in Europe, and have led to flourish physical modelling community worldwide in recent years.

The contribution of Professor Schofield of "From cam-clay to centrifuge models" (Schofield, 1993) is widely recognized in geotechnical community and no need to repeat in this note. Professor Mikasa, who passed away in 2020, read aeronautical engineering in his first degree and turned to a geotechnical engineering professor, engaging development of geotechnical centrifuge for over 40 years. He designed various versions of the centrifuge machine with "*ingenious mechanism* "(Craig, 1995). One of which was equipped with a pseudo-static earthquake loading mechanism (may be named "Mikasa-type centrifuge"). In fact, several centrifuges manufactured in Japan in 1970s were the Mikasa-type centrifuge, including Mark I centrifuge at the Tokyo Institute of Technology, and the first machine at the Public Works Research Institute at Tsukuba.

It has been just over 50 years since 1969. The major trends and key events in centrifuge modelling may be briefly summarized in the following.

As was evident by the fact that all the above-mentioned three papers presented to the 7th ICSMFE dealt with stability problem, such as slope, excavation, tunnel, and retaining structures, as well as bearing capacity problems, formed a major research subject until early 1980s. The method used was a combination of centrifuge modelling, by which failure mechanism can be observed, and the theory of plasticity to produce solutions for a given boundary value problem.

With an advent of modern computer and availability of FEM code, the combination of centrifuge modelling and numerical modelling by FEM has become a standard strategy for solving geotechnical boundary value problems.

Years in 1980s were the period of modelling earthquake and various earthquake actuators were proposed and developed. Dynamic centrifuge modelling has become an indispensable tool for geotechnical earthquake engineering today.

Modelling ocean wave began in early 1990s, opening an interdisciplinary research field of modelling phenomena, involving hydrodynamics phenomena. This trend continues even today and has extended to modelling tsunami events.

Particle Image Velocimetry (PIV) technique originates from an experiment in fluids for a flow visualization technique developed dated back to mid-1980s. Introduction of PIV technique into geotechnical physical modelling in early 2000s (White et al. 2003) has a significant impact on physical modelling community, and PIV technique gains a wide acceptance and has become a standard method for displacement measurement with a high precision.

With rapid developments of periphery technologies such as computer-controlled actuators and devices, robotics, sensitive sensor technology, high resolution and high-speed digital camera and image processing, and wireless technology, recent trends in physical modelling proceeds towards sophistication, automatic controlled system and a higher precision.

A string of successful achievements of centrifuge modelling in the past has created high expectations from society, leading to an important issue of education on how to foster young generation to be able to perform physical modelling with modern highly sophisticated technology environments as well as to be able to understand and utilize the results of physical modelling in geotechnical practice.

The second question is "Which aspect should we focus on?". Contents of research papers on physical modelling typically consist of two parts. Part 1 describes modelling strategy with modelling systems. The modelling strategy includes simplification or idealization of a problem in question, while the modelling systems involve design and development of apparatus, equipment and experimental procedures. Part 2 deals with experimental solutions observed for the problem and discussions on a given boundary value problem. The author believes that the Part 1 is an essential part of research efforts in view of physical modelling, containing scientific originality and providing vital information to other physical modelers. The Part 1 itself must be regarded as a discipline of experimental sciences and should be published independently. This was a key concept behind the International Journal of Physical Modelling in Geotechnics (IJPMG) launched in 2001. In my Editorial on the inaugural issue of the IJPMG in 2001 (Kusakabe, 2001), I wrote that "*Geotechnics is a broad multi-disciplinary of science and technology about the earth and earth materials, including soil mechanics, rock mechanics, geotechnical engineering, earthquake engineering and geo-environmental engineering. Engineers and scientists dealing with geotechnics often use numerical modeling and physical modeling in a complementary manner, to solve a given boundary value problem…..IJPMG aims at covering all areas of physical modelling in geotechnics such as centrifuge model test, shaking table test, pressure chamber test and geo-environmental experiment*."

Dr. Ryan Phillips, then ISSMGE Technical Committee 2 Chair, decided to adopt the name of "Physical Modelling in Geotechnics" for the name of his international conference as International Conference on Physical Modelling in Geotechnics (ICPMG 2002), not Centrifuge 'xx previously adopted. Since then, the international community for physical modelers uses two vehicles, ICPMG and IJPMG for presenting research outcomes and exchanging their ideas. This was the intention at the time of launching IJPMG, "*IJPMG serves as international networking of regular communication forum among physical modelers in geotechnics*." I have, therefore, referred to IJPMG and ICPMG as the major sources of reference in this note and focused on the Part 1of research papers.

The lecture note firstly reviews various viewpoints of the roles of physical modelling in geotechnics, and then presents, not exclusive though, a brief historical development of research subjects in selected topics in centrifuge modelling over half a century. After briefly touching on the issues of similitude, and of large-scale model test under 1 g environment, concluding remarks are presented.

2 ROLES OF PHYSICAL MODELLING

There have been many interesting and penetrating discussions on the role of physical modelling from various aspects.

2.1 Physical modelling in science and engineering

As the proverb goes, "To see is to believe" is always true for studying any physical phenomena. Observation is the starting point for modern science. Kusakabe (2007) wrote that "*Historical development of astrology and physics clearly demonstrates that modern science follows the path where scientists deduce certain laws from careful observation of the nature and compose a comprehensive theoretical model incorporating these deduced laws, to understand the nature in a rational way and also to predict future changes of the nature. Any discrepancy between theoretical prediction and actual observation triggers further improvement of the theoretical model.* He went on that "*Experimental science plays an important role in the observation science. Experimental science utilizes tests in laboratory or field to approximately reproduce natural phenomena*

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to understand corresponding actual phenomena. At the same time, experimental science offers the data to validate theoretical models.

Muir Wood (2002) stated that "*It is a truism that observation forms an indispensable part of the reflective practice loop which underpins engineering and scientific progress.*" Muir Wood (2004) further added that '*reflective practice*' cycle in view of role of physical modeling as *"the physical modelling as forming the observation part of a 'reflective practice' cycle; the theoretical modelling forms part of the prediction.*"

In his early paper, Roscoe (1968) identified two main uses of model testing in soil mechanics. He described that "*The first is to examine, usually on only a qualitative basis, at a reduced scale, the assumptions that have been made in theoretical analyses of prototype problems, the object being to develop analysis and model side by side with a view to improvement of the former.*" "*The second use is to determine, and satisfy, the principles of similitude so that the behavior of a prototype may be correctly predicted from the observation of a model.*"

In his Rankine Lecture Roscoe (1970) described the objectives of Cambridge Research, listing up nine immediate aims (a) to (i) of the Cambridge work, in which he listed up "*(h) to develop centrifugal model test methods so that prototype problems can be studied at reduced scale.*" He concluded that "*The centrifuge will provide much reliable evidence but can never fully replace a properly instrumented full-scale field test".*

Randolph and House (2001) presented a diagram of interaction of physical and numerical modelling in design in the inaugural volume of IJPMG shown in Figure 1, stating that *"In structural engineering, hydraulics and fluid mechanics, physical modelling has largely given way to computational modeling, even in university-based research groups*" and continued that "*The major part of design is generally undertaken through simple conceptual models, which have been developed from correlations with data, or from rigorous numerical analysis. .... Data from full-scale monitoring and from physical modelling are used to calibrate and demonstrate the appropriateness of conceptual models. .... It is relatively rare for physical modelling to be used directly in the design process. More usually, the data from model tests will be used indirectly, vis conceptional models or to validate numerical analyses, which are then used for the design.*"

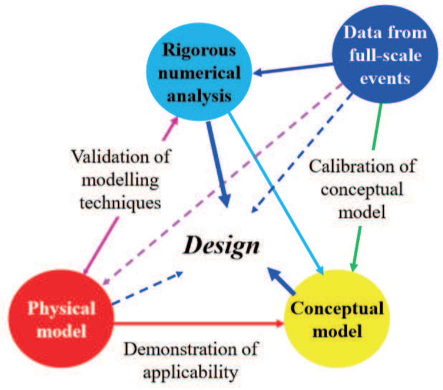

Fig. 1. Interaction of physical and numerical modelling in design (Randolph and House 2001).

Randolph (2017) further elaborated the complementally roles of physical and computational modelling in his 2nd Schofield Lecture in 2017. The complementally role of physical and computational modelling is also echoed by Madabhushi (2015) in his book on centrifuge modelling for civil engineers.

2.2 Physical modeling in geotechnical design

Madabhushi (2015) gave a simplified flowchart for geotechnical design, including the circumstances that centrifuge modelling comes in. Figure 2 is a part of the flowchart.

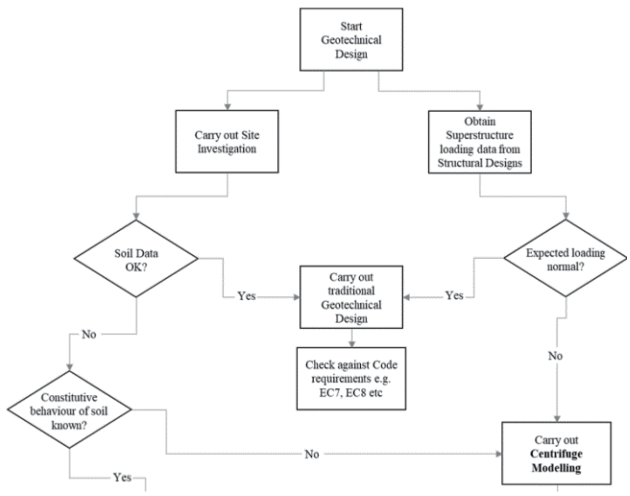

Fig. 2. Simplified flowchart for geotechnical design (Madabhushi 2015).

The flowchart indicates that there are two routes that may require centrifuge modelling. (1) Expected loading is not normal, and (2) Constitutive behaviour of soil is not known. As a role of physical modelling, he mentioned that there are two ways where centrifuge modelling results can be used. The first role is that "*Centrifuge modelling will give rise to data that reveals the essential behavior and the failure mechanisms of the foundations that might occur." "For important or*

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particularly difficult projects, it may be worthwhile to carry out simplified centrifuge testing and use these experimental data to validate the prediction of a FE code. This process can be used to fine tune the FE analyses until the FE code is able to produce matching results to the centrifuge test data." The second role is that "*The data from centrifuge tests together with the observation of failure mechanisms made during centrifuge testing can be used to develop novel design guidelines for particular classes of problems*."

He also noted that "*Performance-based designs in geotechnical engineering reply on to a large extent on our ability to estimate deformations in the ground under the applied loading. It is usually acknowledged that such an estimate of deformations is in general more challenging than performing a safety factor-based design using the concepts of ultimate limit state*."

Gourvenec (2018) discussed an interesting and challenging topic of the role of centrifuge modelling in capturing whole-life responses of geotechnical infrastructure to optimize design, taking an offshore structure as an example from installation stage to decommissioning. He wrote that "*The time frames relevant to modelling a whole-life response, on which design guidance could be based, are impractical for laboratory floor or field testing. Tens of cycles of consolidation are required, which involve durations that are impractical to conduct in the field or in model tests at laboratory scale-centrifuge testing is necessary.* He presented a pyramid of activities in the trajectory from a conceptional idea to implementation of a design method in engineering practice. In real situations, various phenomena may occur during the whole-life such as chemical reactions and delayed compression, which pose a difficulty in modelling of time-scaling.

2.3 Physical modelling in observation method

Schofield (2000) gave his view that "*Geotechnical centrifuge model testing complements the observational method." and* argued that *"Centrifuge tests now solve problems where observation at full scale is no help*.", and *"Our (centrifuge) tests complement observational methods, with larger strains and more extensive parametric studies than are achieved in the field*."

The observational method has been widely used in construction practice. Eurocode 2.7 Observational method (2004) states that "*When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as "the observational method", in which the design is reviewed during construction*".

In his Rankine Lecture Peck (1969) described that "*the complete application of the (observational) method embodies the following ingredients.*

(a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
(b) Assessment of the most probable conditions and the most unfavorable conceivable deviation from these conditions. In this assessment geology often plays a major role.
(c) Establishment of the design based on a working hypothesis of behavior anticipated under the most probable conditions.
(d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.
(e) Calculation of values of the same quantities under the most unfavorable conditions compatible with the available data concerning the subsurface conditions.
(f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those projected on the basis of the working hypothesis.
(g) Measurement of quantities to be observed and evaluation of actual conditions.
(h) Modification of design to suit actual conditions."

Geotechnical centrifuge model testing could contribute to the processes of (c), (d) and probably (f).

Peck noted that *"It (the observational method) can be used only if the design can be altered during construction. This essential feature often introduces complications into contractual relations. .... The possibility of having to slow down construction is a drawback inherent in the method".*

As reflected in the Eurocode, the original concept of the observation method is considered to modify the initial plan based on the measurements of the behavior during the progress of a project. Decision must be made in a limited short period of time. If that is the case, it may be unrealistic to plan and perform a series of physical model test and offer an answer to the needs in question arising during construction. It may be more practical that prior to the project starts, a series of tests is performed, covering a wide range of scenarios that the project might encounter during the project in advance, and provide a template to compare with measurement results to assist the decision-making. This type of approach may become feasible under design and build procurement systems.

2.4 Physical modelling in geotechnical risk assessment

Davies et al. (2010) discussed the role of physical modelling of natural hazards. They argued that *"Physical model testing can also be used to validate analytical and numerical methods and assess techniques for hazard reduction or rehabilitation",* by studying *"reliable triggering mechanism of natural hazard that initiated the phenomenon or subsequent mechanisms* *developed in the immediate aftermath of the trigger"*. They pointed out that physical modelling approach has advantages over field observation. Since the field observation can be done only after a catastrophic event, it is not always possible to establish the triggering mechanism. Long term monitoring is not generally possible to determine when and where a physical event will result.

Their paper focused on the phenomena of sliding slopes, earthquake fault rupture and permafrost degradation. One of the most difficult scaling issues, they admitted, is that the scale of actual phenomena is too large to model satisfactory in a physical model. They gave a critical comment against large-scale model tests, which will be discussed later.

Natural disaster is diverse, including sink hole, rainfall related disaster, debris flow, tsunami disaster, liquefied lateral flow, other than three topics they discussed. Obviously geotechnical engineering alone is not adequate to fully understand natural disasters. Collaboration with other disciplines such as geology, topography, sedimentology, meteorology is of primary importance.

2.5 Physical modelling in industry

Physical modelling is merely an academic interest but must contribute to society. Gaudin et al. (2010) discussed an interesting issue of physical modelling with industry. They presented the observation based on the experiences of three long-established centrifuge modelling facilities: the Centre for Offshore Foundation Systems at UWA, Deltares, and the Laboratoire Central des Ponts et Chaussées. They noted that three types of funding can be distinguished for physical modelling research.

Type1. Competitive public research funding from fundamental or applied research.
Type2. Project oriented research commissioned by the government.
Type3. Direct industry funded research.

Type 1 funding is in most cases from science council or other research funding organizations. A good example of Type 2 funding may be found in his paper by Kitazume (2009).

There are, in fact, two modes of flow of funding, in relation to Type 3. Mode A and Mode B may be considered in relation between industry and research institute with respect to the flow of funding and the availability of facilities/expertise. Mode A is a situation where facilities/expertise belong to university/higher educational institute, while Mode B is the other way round, industry has facilities/expertise.

The discussion by Gaudin et al. focused on Mode A, where industry has a need to obtain a solution but has no research facilities/expertise on a particular field, and industry can provide research funding to a research institute where facilities/ expertise is available. Mode B is that industry owns research facilities/expertise, and the flow of funding is an opposite direction. As was pointed out by Kimura (1998), the Japanese centrifuge community has grown differently from other major countries, and several large contractors and consultants own a research center equipped with their centrifuge facility, and Mode B is very much in common in Japan. Terashi et al. (2004) explained the background of centrifuge boom in Japan at that period of time.

There must be, at least, a few hundreds of Japanese civil engineers who have had an experience of using centrifuge modelling during their university days, graduated from Osaka City University, Tokyo Institute of Technology, Chuo University, Kyoto University, and many other universities which own centrifuge facilities. Some of them have joined the above-mentioned large constructors and consultants and play a key role in their research center.

As for consultant practice, Terashi et al. (2004) described ten years operation of centrifuge at a consulting firm, Nikken Sekkei Nakase Geotechnical Institute (NNGI). Nikken Sekkei is one of the largest consulting firms in Japan. They described that "*The activity of NNGI may be divided roughly into three: self-initiated research, commission research, and technical support for the design or construction control carried out by the group companies. ……. When centrifuge modelling is involved, the research starts from the basic understanding of physical phenomenon and may include modelling of models and parametric studies. The difference is time. Time span for each topic may be three years at longest. ……Normally the contract is given by a fiscal year basis. Again, when the physical modelling is involved, there is scarcely a time allocated to manufacture new test equipment.*" "*Centrifuge model tests are often carried out at the prototype scale. However, to the authors' knowledge, the simulation of a specific prototype has never been done so far and there is no real-life project designed by centrifuge modeling alone.*"

Mode B has a merit for contractors in many ways. Through research contracts with research institutes and universities, there is a flow of updated professional knowledge and research needs from research institutes and universities to the contractor, together with getting funds to run facilities. Research contract with other sectors is also possible. Contractors have always incoming/ongoing construction projects. The research group can swiftly support the project when some issues arise. This cycle of project management provides advantages of bidding, profitability and competitiveness in industry, especially under design and build procurement systems.

Let us take an example. Obayashi is one of the major contractors in Japan and owns the research center with a wide range of research facilities, including a large geotechnical centrifuge of 700 g-ton with a sophisticated dynamic test capability (Matsuda and Higuchi, 2002). They have been operating the facility and published more than 100 papers over 20 years for geotechnical and structural modelling.

Counterparts of research collaboration are as many as 17 universities and national research institutes, including Port and Airport Research Institute, Railway Technical Research Institute, Central Research Institute of Electric Power Industry. Funding comes from government, local government, electric company, railway company and various research consortiums consisting of many private companies.

The areas of research are classified into 6 categories as is presented in Figure 3. Foundation & Retaining structure shares 45.9 %, followed by Excavation and Underground structure (28.6 %), Earth structure and slope (8.2 %), Soil reinforcement and soil improvement (6.0 %), Super structure (5.3 %), and others.

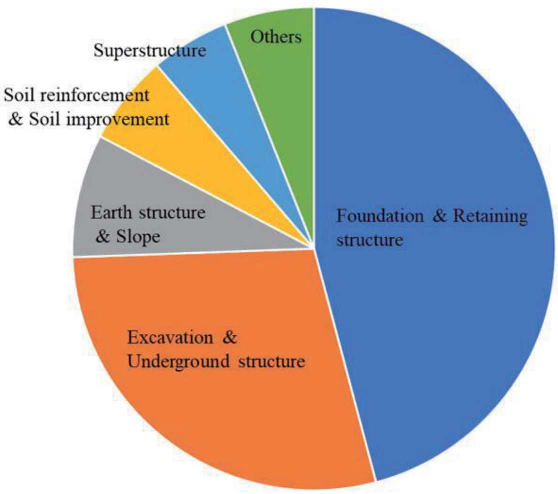

Fig. 3. Research areas at Obayashi research center (Tomiyasu 2020).

The pie diagram of Figure 4 shows the objectives of these model tests. Elucidation of phenomenon shares almost a half (46.1 %), followed by development of design method (36.5 %), development of construction method (9.6 %) and consulting including design for a specific project (6.9 %).

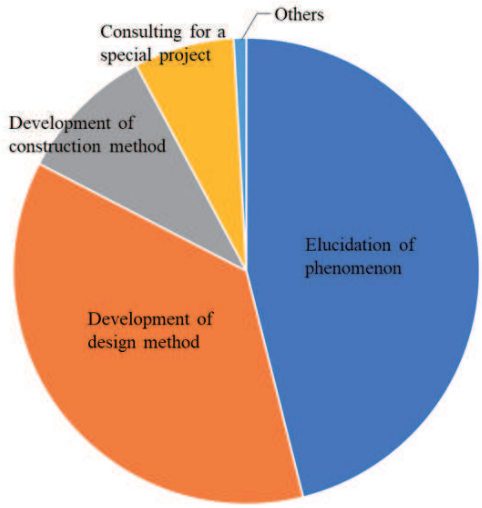

Fig. 4. Objevtives of centrifuge model tests at Obayashi research center (Tomiyasu 2020).

3 DEVELOPMENT OF MODELLING TECHNIQUES

3.1 Physical modelling community—formation and growth

a) Formation

The information was given to the author by Taylor (2020) who summarized the brief history of how the physical modelling community has been formulated within ISSMGE based on Council Meeting minutes over four decades as follows.

"1981 (Stockholm): Niels Krebs Ovesen introduced a proposal from the British and Danish Geotechnical Societies for the establishment of a sub-committee on the use of centrifuges in geotechnical model testing. The recommendation was accepted without dissent. 1983 (Paris European Conference): Victor de Mello presents a report on Technical Committees that he is creating and refers to the "newly formed Centrifuge Testing Committee" chaired by Andrew Schofield. 1985 (San Francisco): Andrew Schofield presents a report on the committee and the report is simply titled "Centrifuges". 1987 (Dublin European Conference): Bengt Broms presents a report on TCs and refers to "TC2 Centrifuge Testing". This title remains in use 1997 (Hamburg conference). 1999 (Amsterdam European Conference): Ryan Phillips reported that TC2 had been renamed "Centrifuge and Physical Model Testing" to reflect more closely its activity. 2001 (Istanbul): The TC2 is referred to as "Physical Modelling and Centrifuge Testing". 2003 (Prague European Conference): William Van Impe refers to "TC2 Geotechnics of physical modelling and centrifuge testing". 2005 (Osaka): The reference is to TC2: Physical Modelling in Geotechnics (Colin Leung). This title is also used in 2007 and 2009. 2011 (Toronto Pan-

American Regional Conference): Jean-Louis Briaud created the Technical Oversight Committee in 2009 and probably in early 2011, all TCs were renumbered and sometimes renamed. At the Toronto Council Meeting, there is reference to TC104 Physical modelling in Geotechnics. That has not changed since.

In summary, the idea of a Centrifuge committee starts in 1981 and becomes a reality in 2003. The numbering of committees starts in 1987 (to TC2). Eighteen years after the first idea, "physical modelling" was recognised (i.e., not just centrifuges). In 2011, TCs were categorised into Fundamentals, Applications and Impact on Society and then renumbered."

b) Growth

Establishment of Technical Committee TC 2 on Centrifuge Testing in 1983 created a momentum to form and grow the physical modelling community in ISSMGE. TC 2 organized workshops held in Manchester, California, and Tokyo in 1984. The workshop held in Tokyo attracted 17 authors from six countries. The recent ICPMG 2018 attracted 560 authors from 37 countries. The numbers of author and country have significantly increased by 33 times and 6 times over 34 years, respectively

3.2 Historical development

Historical development of centrifuge modelling over half a century is overviewed in the following six areas. A simple chart is presented, not exclusive though, when appropriate. These charts may help beginners of physical modelling to grasp a stream and direction of the development.

a) Model preparation
b) Soil characterization
c) Modelling construction sequence
d) Modelling earthquake
e) Modelling ocean wave
f) Modelling tsunami events

a) Model preparation

(i) Preparation of clay model

Soil structure

The Earth is covered by various materials: soil, rock, ice, and water. Since human activities largely concentrate on/in sedimentary areas, which consist of young clay and sand deposits. A great number of soil model used in physical modelling in geotechnics so far are either reconstituted, consolidated saturated clay or air-pluviated dry/saturated sand. A comparatively small number of studies focus on other geotechnical materials such as jointed rocks, weathered residual soils, and talus deposits, which are subjected to physical and chemical weathering and erosion, often causing instability of slope.

Model preparation is of primary importance to any model tests. Although experimental procedures for preparing reconstituted, consolidated saturated clay and air-pluviated dry/saturated sand have been well established and widely accepted among the centrifuge community, it may be appropriate to review some previous efforts.

b) Undisturbed or Reconstituted/ Young or Aged clay

Soil used in centrifuge tests is either undisturbed or reconstituted soils. In early days, undisturbed natural soil samples were often used for centrifuge tests. For example, Lyndon and Schofield (1970) reported the modelling short-term failure of London Clay. A large undisturbed sample of 700 mm in diameter and 400 mm deep of firm to stiff weathered London clay of approximately 1/3-ton mass was recovered from a construction site at a depth of 2 m below ground level and subjected to consolidation under 66 g for 16 hours. When the machine stopped in operation, the cut slopes were made, and the soil model was back under the centrifuge acceleration of 66 g, and they observed the failure of the steeper slope after 55 min.

Craig and Yildrim (1976) described a similar case of trench excavation failure using a large undisturbed block sample of the clay obtained from a point on the side a few meters from the failure in a rectangular steel sampler. This block was used in the formation of three different trench models. After pre-consolidating the entire block in the centrifuge at 30 g, the centrifuge machine was brought to a halt and a cutting 0.670 x 0.150 m in plane, 0.140 m deep was made at one edge. The model was subsequently subjected to incremental increase in centrifuge acceleration up to 75 g without any signs of failure. After being halted again for close inspection, the model was finally brought to failure under increasing acceleration when collapse occurred in the form of substantial earth falls from the face at a simulate depth of 11 m.

Reasons for using undisturbed soil may be stemmed from the recognition of importance of soil structures. Leroueil and Vaughan (1990) comprehensively reviewed a large body of experimental evidence of soil structured observed in different geomaterials, including soft clays, stiff over-consolidated clay, clay-shale and weak mudstones, sands, weak rocks, and residual soils, concluding that most natural geomaterials are structured and the effects of structure are as important in determining engineering behaviour as are the effects of initial porosity and stress history.

Modelling the behaviour of natural geomaterials has three aspects, initial porosity, stress history and structure. Taylor (1995) noted that *"Reproducing the consolidation history is not especially difficult"*. How about 'structure'? Taylor (1995) went on that

"Modelling of specific sites requires the recovery of field samples. This could be in the form of intact blocks which are then trimmed to size and loaded in centrifuge containers for subsequent reconsolidation on the centrifuge and testing. Alternatively, the site soil could be reconstituted and consolidated such that the profile of effective stress history in the model corresponded to the prototype." For latter modelling, he described that "*any 'structure' or 'fabric' present in the field sample is likely to be destroyed by this process and some attempt at ageing of the sample may be necessary if all aspects of the prototype behavior are to be replicated."*

Phillips (1995) also pointed out that *"Macro-fabric present in the undisturbed model sample, such as structure, fissures, inclusions and potential drainage paths, may not scale to be representative of the conditions in the prototype."*

Due to difficulty in retrieving undisturbed block sample at site and due to some ambiguity of stress history of undisturbed soil samples during the process of centrifuge testing, limited test cases using undisturbed soils were reported. Among them, Fujii et al. (1988) reported the case of direct comparison between large-scale field test and centrifuge test using undisturbed granular soils.

A current trend seems to use reconstituted soil. In his Rankin Lecture Schofield (1980) stated that *"Tests on natural soil proved very useful, but our achievements with remoulded soil are important to use as a group principally concerned with teaching experimental and theoretical soil mechanics"*. In fact, a combination of centrifuge tests using remoulded clay models and the theory of plasticity had achieved a string of successful outcomes for undrained stability of tunnel in clay (Mair, 1979), of vertical shaft in clay (Kusakabe, 1982) and others.

Currently a general trend is to use remoulded soil, using industrial clay such as kaolin or remoulded from natural clay deposits, which has an advantage of consistent production, ensuring repeatability of the test and is appropriate for parametric study. Randolph (2017) suggested that it is advisable to recover the soil from the local site if the test results are intended to use towards field application.

In real situations, however, effects of ageing and some degree of cementing at grain contacts have an important influence on behavior as are evident in the literature (Leroueil and Vaughan, 1990, Tan et al., 2003, 2007).

Reconstituted (remoulded) clay model is 'a young deposit.' Natural deposit experiences the reduction in volume at unchanged effective stresses. Bjerrum (1967) reviewed the various geological processes which can take place with time in the Norwegian normally consolidated marine clay and presented a concept of delayed compression. Delayed compression leads to the development of a reserve resistance against compression under additional loads. Effect of time on compressibility cannot be described by a single curve in an *e*-log*p* diagram but requires a system of lines or curves, a unique relationship between void ratio, overburden pressure and time. The aged clay is characterized by the increase of consolidation yield stress and the decrease of void ratios due to delayed compression. *e*-log*p* curve has a sharp bend and the virgin compression curve concave downward for normally aged clay, while young clay has a gentle *e*-log*p* curve.

Leroueil and Vaughan (1990) described the behavior of structured soil such that usually the structured soils have characteristics due to bonded structure and its effects follow a simple general pattern that involves stiffer behaviour followed by yield.

Possible methods to reproduce the structured soil may be to use either 'thermal effect' or 'chemical bonding effect'. Tsuchida et al. (1991) developed "*a promising technique*" (Taylor, 1995) for creating aged, remoulded clay sample in laboratory. The procedure for reproducing the structure of aged clay in laboratory is to prepare a sample by consolidating clay sample at a high temperature. The consolidation cell was surrounded by hot water whose temperature was controlled at 75 degrees Celsius by an electric heater. After the completion of consolidation under the final consolidation pressure, the sample was unloaded and cooled at the room temperature of 25 degrees Celsius. By consolidating clay slurry at a high temperature and cooling after the completion of consolidation, mechanical properties of the remoulded clay sample are similar to that of lightly aged clay. The acceleration of the cementation action is considered to be the main causes of the effect of the high temperature consolidation. The procedures seem to be useful for carrying out models when one intends to simulate the behavior of natural clay using remounted clay.

Kitazume and Terashi (1994) used the procedure of high temperature consolidation technique to make a model of slope for their centrifuge tests. Two kinds of clay samples were prepared. One was consolidated at a room temperature (R-clay) and the other was consolidated at a high temperature of 75 degree Celsius (H-clay). The model slope of H clay failed suddenly, and the deformation was concentrated along a sliding surface, while the model of R clay failed after large deformation of the whole model. The slope of H clay shows brittle behavior analogous to natural slopes. This interesting method, however, did not gain popularity among centrifuge modelers. In recent years, a method of mixing chemical agent remoulded clay is adopted to replicate the structured clay soil, such as the work by Hatanaka and Isobe (2018) who attempted to study of long-term consolidation after earthquake.

Theoretical modelling approach for structured clay seems more advance for understating field behaviour. For example, Asaoka et al. (2000a, 2000b) extended the original Cam-clay model by introducing a 'super-loading yield surface concept', together with Hashiguchi's subloading yield surface concept in order to describe the elasto-plastic behaviour of structured and over-consolidated soils.

The theoretical study using this constitutive model explained well the field observation of pore water pressure rises in a soft clay layer at site 20 years after the embankment construction, which is contrary to the common belief among geotechnical engineers (Asaoka, 2009).

Importance of structured soil has become evident that the long-term behaviour of structured clay deposited after experiencing an earthquake exhibits peculiar phenomena which cannot be properly explained based on the original Cam-clay type constitutive modelling (Asaoka, 2009, Noda et al., 2009).

How would physical modelling approach respond to a '*prophecy*' by theoretical modelling approach? How could physical modelling approach to offer reliable data to theoretical modelling approach for validation?

Surface crust

Selecting an appropriate combination of a pre-consolidation pressure on laboratory floor and a centrifuge acceleration, it would be a relatively straightforward problem to reproduce a desired clay strength profile with depth in a reduced model, from a normally consolidated model in full depth of the model (e.g., Kimura et al., 1984), to over-consolidated layer overlying a normally consolidated ground of which strength increases with depth (e.g., Davies and Parry, 1985), and over-consolidated model in full depth (e.g., Mair,1979). A slightly more challenging task to reproduce the layered nature occasionally encountered in the field such as a surface crust overlying a normally consolidated clay.

To create a surface clay layer overlying a normally consolidated clay layer, different techniques have been attempted; combination of various stress histories, partial drainage during centrifuge consolidation, changing pre-consolidation pressures with depth on the laboratory floor before centrifuge consolidation, and separate preparation of two layers; one on the laboratory floor and the other in centrifuge, subsequently combine the two layers together.

The first attempt for creating a surface crust in a centrifuge was by the work by Davies (1981) and reported by Davies and Parry (1985). Three stages of consolidation were adopted: firstly, consolidation on the laboratory floor under 50 kPa, secondly, centrifuge consolidation at 20 g with a total consolidation pressure of a surcharge and a sand layer on the surface of 52.3 kPa and finally, centrifuge consolidation at 100 g with the sand layer of 8 kPa.

Almeida and Parry (1984) focused on a phenomenon of partial consolidation. They prepared a soil model consisting of a layered foundation of Gault clay overlying kaolin clay. The method they used was in the following. The kaolin slurry was placed in a container and Gault clay slurry was placed on the top of the kaolin slurry. Two layered clay model was consolidated. After the completion of the pre-determined consolidation, the partial drainage consolidation was carried out to produce a stiff crust at the upper part of the clay model in the laboratory floor. The clay model was then unloaded and transferred to a strong box for centrifuge test, subjected to centrifuge consolidation.

Nakase et al. (1987) used a single soil material with a combination of laboratory consolidation and centrifuge consolidation. They adopted two-stages consolidation on the laboratory floor. The first-stage consolidation was carried out on the laboratory floor in one or four layers to make a crust layer. In the case of the four-layered consolidation, consolidation pressures were gradually decreased as shown in Figure 5.

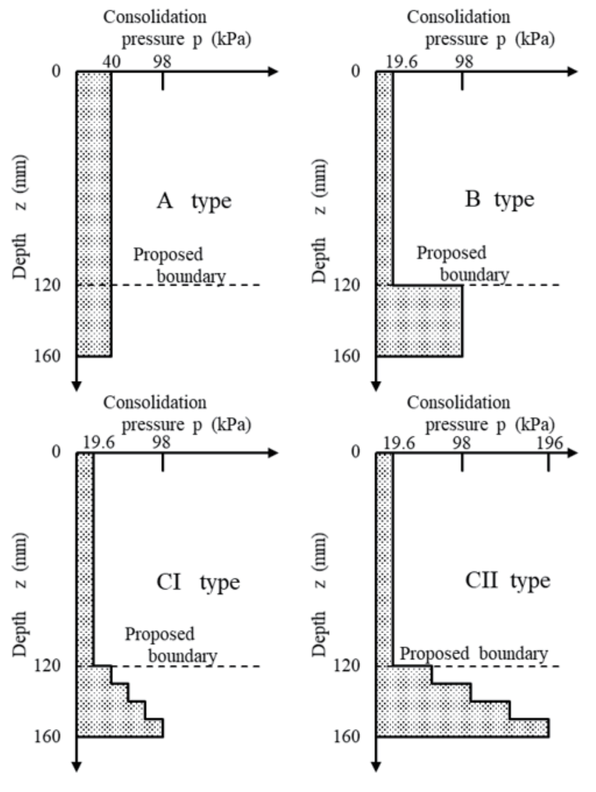

Fig. 5. Preparation of surface crust (Nakase et al. 1987).

After the first-stage consolidation, additional amount of slurry was poured and the second-stage consolidation was conducted to form a complete thickness of the model. The soil container was then turned upside down and mounted on a centrifuge subjected to centrifuge consolidation.

In the study of deep-penetrating spudcan foundations on layered clays, Hossain and Randolph (2010) developed a method for creating a stiff-soft clay profile in a drum centrifuge. They prepared two layers of clay separately. Top crust was consolidated on the laboratory floor, and the bottom normally consolidated clay was created under centrifugal acceleration, and then placing the top layer onto the normally consolidated. Hossain et al. (2014) tried to simulate the seabed conditions encountered in some locations of Australia's North-West Shelf and developed a new technique for reconstituting a thin crust layer for model testing in layered sediments. The artificial crust was created using commercially available Plaster of Paris mixed with reconstituted silt, which enables to reconstitute upper crust with strength one order of magnitude higher than the underlying soil.

Lozada et al. (2018) studied the bearing capacity of footing resting on unsaturated desiccated soils, which is found within the first few meters of highly plasticity clays of Bogota, in Colombia. The over-consolidated layer was prepared in two layers by compaction with the optimum water content and subjected to static compression. The normally consolidated clay prepared separately under 1 g environment is placed over the compacted over-consolidated layer. The container was then overturned and subjected to loading test, presumably without centrifuge consolidation process. Salehi et al. (2018) also examined the undrained bearing capacity of a footing on a layered clay deposit. The kaolin clay slurry was consolidated in two centrifuge boxes at two different maximum stress levels to obtain a soft and stiff clay layer on the laboratory floor. After pre-consolidation process was completed, the stiff layer was removed from the centrifuge box and a slice of the stiff layer was cut and placed on the top of the soft clay sample. The entire sample was then ramped up to a centrifuge acceleration for a period of 24 hours.

The review of previous studies demonstrates a room for further development of creating a multi-layered clay soil profile.

(ii) Preparation of sand model

During the term of Prof. Kimura's chairmanship of TC2 in ISSMGE, a working group was formed in Japanese Geotechnical Society (JGS), which conducted a questionnaire survey on method for preparation of sand sample. The questionnaire was sent to 49 centrifuge users across the world in 1997, followed by a cooperative test on the method with the participation of 18 institutions. The results were summarized in a report published in 2000 (JGS TC2 committee, 2000).

In early days, tamping or vibration method was used to prepare dry sand model (e.g., Yamaguchi et al. 1976). At the time of the questionnaire survey in 1997, it was found that air pluviation method was widely adopted (pluviation method 76 %, and vibration method 18 %).

The JGS TC2 classified types of pluviation method: spot-type, line-type and plane-type. TC2 report concluded that the density obtained by pluviation highly depended on both pouring mass and pouring height. Reproducibility of the spot-type and the line-type are almost the same and better than that of the plane-type regardless of container size. As for the distribution of the density in the horizontal direction, the line-type gave better uniformity than the spot-type and the plane-type. The paper by Madabhushi et al. (2006) suggested that the preparation of sand model is still an important issue in physical modelling.

Four issues related to preparation of sand model in centrifuge are (1) soil fabric, (2) swing-up compression, (3) cross-anisotropy, (4) inhomogeneity, and (5) saturation.

Soil fabric

In his Rankine Lecture Ishihara (1993) discussed an importance on the method of sample preparation, stating that *"different methods of sample reconstitution have been known to create different fabric, thereby yielding different responses to load application"*. He explained that "three kinds of procedure are widely used for the preparation of sample of sand for laboratory testing", which are illustrated in Figure 6.

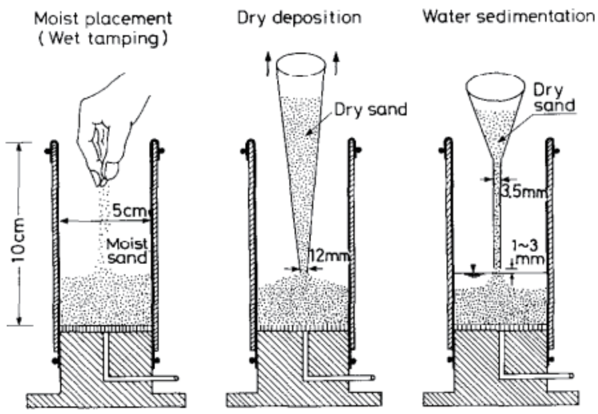

Fig. 6. Three methods of sample preparation (Ishihara 1993).

Interesting to note is that he wrote that "*the air pluviation method is known to produce samples that are always dilative and has not been used in the present study"*. This means that there is a difference of sample preparation method used between laboratory testing and centrifuge testing as far as liquefaction study is concerned.

Swing-up compression

In addition to initial void ratio prepared in laboratory in 1g field, centrifuge sand model is subsequently subjected to centrifugal acceleration, causing slight densification of the sample (swing-up compression). The report prepared by JGS TC committee pointed out that

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in some organizations, it is standard practice to adopt a number of ramp-up and ramp-down cycles (g cycles) prior to any testing. The first few cycles have been shown to cause slight densification of sample, particularly in relatively loose sands. About five g cycles appear to be required to prevent further compression (Ueno et al., 1994). The merit for the g cycles is to improve the reproducibility of test results (Ueno et al., 1994). Ueno et al. also found that the void ratios under an acceleration of 100g are approximately expressed by the following liner equation, for the initial void ratio, e_o, ranging from 0.674 – 0.774 (the relative density Dr. of 81.3 – 55.1 %) for Toyoura sand.

$$e = 0.92e_0 + 0.041$$

Madabhushi et al. (2018) studied swing-up compression, measuring change of density with depth by using a PIV measurement, which confirmed that it is small but not necessarily negligible. They found that the average change in voids ratio during swing-up was found to be -0.012. For Ottawa sand, this translates into a 4 % densification in terms of relative density Dr.

Cross- anisotropy

One of the issues is anisotropy of the sand model prepared by pluviation method. Oda and Koishikawa (1977), Oda et al. (1978) showed that fabric anisotropy due to the parallel alignment of particles is universally observed not only in naturally deposits, such as river, beach and dune sands, but also in artificially deposited sands. This is because a major plane of each elliptical particle tends to arrange nearly parallel to the horizontal. The plane characterized by the paralleled alignment of elliptical particles is called bedding plane. Inclination angle δ of maximum principal stress axis to the bedding plane is defined as shown in Figure 7.

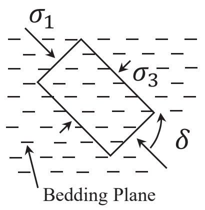

Fig. 7. Inclination angle δ of maximum principal axis to bedding plane.

Anisotropy of sand has a significant influence on bearing capacity. Oda and Koishikawa (1977) reported the loading test of a footing on dry dense sand using a small box of 300 mm long, 70 mm wide and 200 mm depth under 1 g environment. Kimura et al. (1979) carried out the similar set of loading test of a footing on dry sand under centrifuge acceleration of 30 g. In their tests, two kinds of model soil were made by a pouring method; H case refers to the case where the plane of bedding is parallel to the direction of load application, while V case refers to the case where the load is applied in the direction perpendicular to that of the bedding plane.

The test results indicated that the ultimate bearing capacities for the V case are slightly larger than those for the H case, but no difference in the ultimate bearing capacity is apparent for the small value of relative density. It is interesting to note that the settlements at peak load for the H case are noticeable larger than those of the V case regardless of the relative density Dr values. The slip lines detected by X-ray radiographs revealed that the slip lines for the V case extend to greater depth and the model of the H case fails at relatively shallow depth.

The effect of anisotropy on seismic response of retaining wall was investigated for both dry and saturated sand model (Zeng and Min, 2010), where three different deposition angles, 0, 45 and 90 degrees were selected. The model preparation was the air pluviation method, pouring dry sand into a tilted model container, similar to the method adopted by Oda and Koishikawa (1977). The tests were conducted under 50 g. More recently, the effect of anisotropy on liquefaction behaviour was examined by Ueda et al. (2019) in a centrifuge.

Inhomogeneity of soil deposits

A soil deposit is neither uniform nor consists of continuous layers. The actual soil profile characterized by various patterns of layering and lensing is very complex. Maharjan and Takahashi (2013) compared liquefaction-induced settlement and pore water migration among four types of soil model tests under seismic excitation; one is a uniform soil deposit; one is a continuous layered soil deposit; and two are discontinuous layered soil deposits, as shown in Figure 8.

Inhomogeneity was incorporated by including periodically distributed discontinuous silty sand patches. They observed that the rapid dissipation of excess pore pressure through discontinuous parts in the non-homogeneous soil deposits caused non-uniform settlement.

They used Toyoura sand as fine sand and Silica No.8 as silty sand, of which permeability is ten times less than that of Toyoura sand. The models were prepared by air pluviation method. Toyoura sand was deposited first with the help of two lightweight bricks placed on both sides. Then the remaining parts were filled with Silica sand No.8 by air pluviation method, forming trapezoidal silty patches as illustrated in Figure 9.

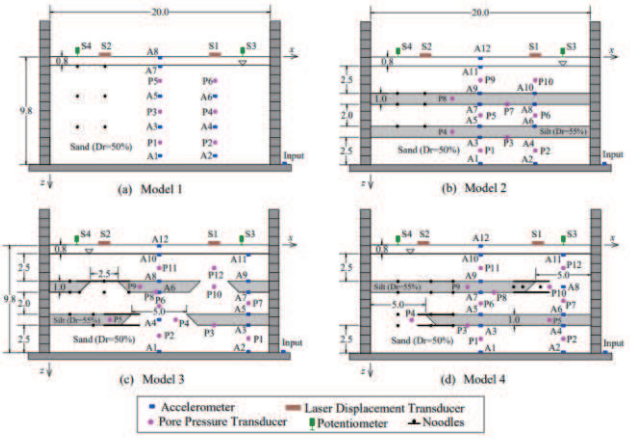

Fig. 8. Non-homogenous model soil deposits (Maharjan and Takahashi 2013).

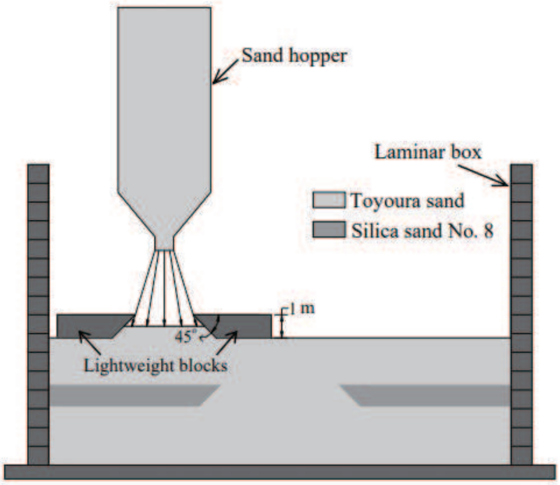

Fig. 9. Model preparation of non-homogenous soil deposit (Maharjan and Takahashi 2013).

With the similar non-homogenous soil deposits, Maharjan and Takahashi (2014) examined liquefaction-induced deformation of earthen embankments under sequential ground motions.

Soil improvement techniques also create artificial non-homogenous soil deposits. Industrial development of coastal areas in Japan where soft clay deposits widely prevail, has necessitated the development of effective soil improvement method. Centrifuge technology has played an important role in understanding the behaviour of soft clay and improved ground, and in establishing design methods.

Soil improvement methods currently widely used are sand compaction piles method (SCPs) and deep mixing method (DMM), both of which were developed in Japan. Since the installation of these soil improvement methods involves a series of construction sequences, there is a big challenge for centrifuge modelling.

Kusakabe (2002) gave a review of centrifuge modelling of SCPs and DMM and discussed how the present modelling techniques are close to reality. The central issue of discussion has been how to install SCPs or DMM in centrifuge models.

Kimura et al. (1983) developed a method for preparing the improved ground by SCPs. Model sand compaction piles are made in test tubes. A fishing line is put into the test tubes and deaired water is poured to the tube. Saturated sand is then poured into the test tube and subjected to vibration until the specific density is attained. Having frozen the tube with sand in a refrigerator, the test tube is broken, and the frozen sand piles are carried to the model ground by holding the fishing line. Finally frozen sand piles are inserted into the holes previously augured and left for gradual thawing. This method with some modifications has gained a wide acceptance for its simplicity and applicability for higher replacement ratios up to 70 % (e.g., Takemura et al., 1991). However, this method ignores the process of expanding the pile diameter by re-driving by a hammer in the field. Ng et al. (1998) developed an in-flight sand SCPs installer.

Springman (2014) tabulated the set-up of the centrifuge model tests previously conducted on SCPs from the past international conferences, including the installation method of SCPs and discussed on how representative their stress histories are.

Mixed-in-place chemical columns such as DMM seems more difficult to model. Models of DMM were made of acrylic pipes instead of soil and cement (Kitazume et al., 2012), or light-weight precast concrete (Kitazume, 2016). There are a few challenges for in-flight modelling of chemical columns. Lee et al. (2006) reported the DMM modelling in centrifuge by using an in-flight DM apparatus, modifying the in-flight sand compaction piles previously described. The model blade has only one layer of cutting and mixing. Kitazume et al. (2012) described an in-flight grout injection system.

Saturation

Degree of saturation is a critical parameter in the study of liquefaction both for laboratory tests and physical model tests. It is well known that the liquefaction resistance increases significantly with a decrease in degree of saturation (e.g., Yoshimi et al. 1989). Okamura and Soga (2006) demonstrated that the liquefaction resistance of unsaturated sand depends on the effective confining stress and proposed the concept of potential volumetric strain.

Physical modelling points of view, there are two important challenges which are how to saturate soil models, and how to evaluate the degree of saturation of prepared soil models.

Takahashi et al. (2006) compared three different preparation methods to prepare fully saturated soil models by fluid percolation technique, which are Atmosphere technique, Vacuum technique, and Carbon dioxide gas and vacuum technique, as are illustrated in Figure 10.

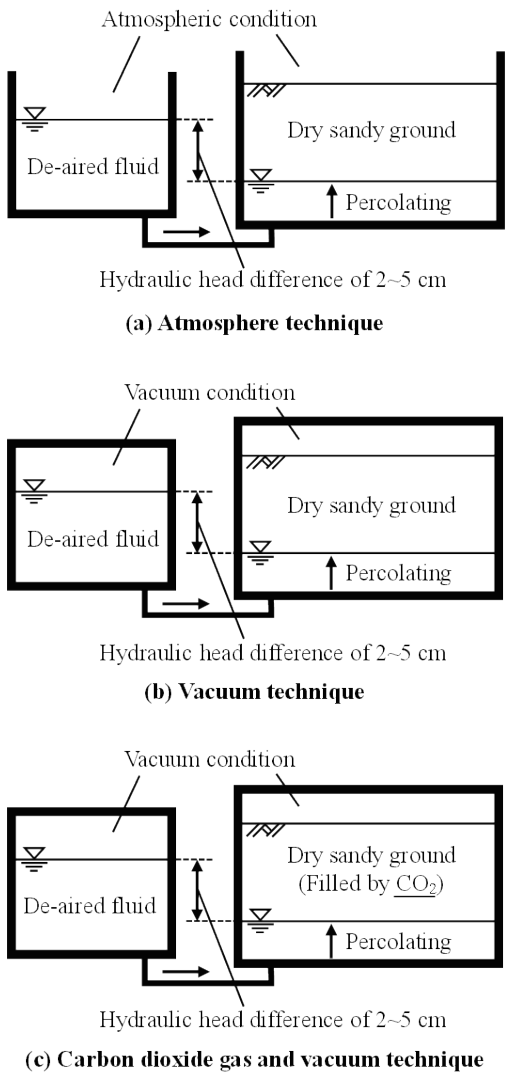

Fig. 10. Three methods for saturation of sandy ground (Takahashi et al. 2006).

They used two methods for obtaining the degree of saturation Sr of the model ground. One is to measure the weight and volume of dry and saturated model ground and the other is to estimate the degree of saturation by measuring P-wave velocity propagating through the model ground, using the relationships between P-wave velocity and Skempton's pore pressure coefficient B-value, theoretically derived by Kokusho (2000) and Tsukamoto et al. (2002). The conclusion they arrived is that the Carbon dioxide gas and vacuum technique is the most suitable technique for preparing saturated model ground among the three techniques described above.

Okamura and Inoue (2012) developed a method for high-resolution measurement of degree of saturation as is given in Figure11, by precise measurement of the change of the water table during the change in the air pressure in the chamber. The change of the water table can be measured by using a light-emitting diode (LED) displacement sensor with a resolution of 10μm or higher. They successfully measured the degree of saturation of model ground with an accuracy of 0.1 % and higher. To carry out this process in a centrifuge, this method ensures the consistent production of fully saturated sand model for liquefaction study.

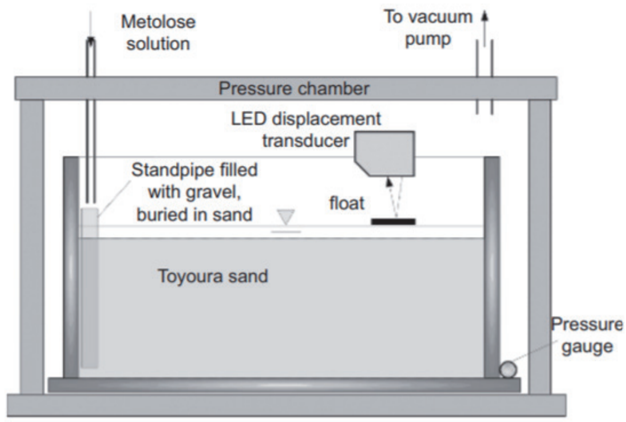

Fig. 11. System for saturation of sand model (Okamura and Inoue 2012).

Beneficial effects of reducing the degree of saturation on the liquefaction resistance can be obtained either by lowering the ground water table or by injecting air bubbles into soil pores. Takemura et al. (2008) conducted a series of centrifuge tests to examine the effects of process of lowering and recovering ground water table in sandy ground. Marasini and Okamura (2015) developed a system in which air is injected into the soil in-flight and demonstrated the effectiveness of air injection technique for mitigating liquefaction under light structures. Zeybek and Madabhushi (2017) also conducted a series of centrifuge tests on air injection technique.

b) Soil characterization

Once the model is prepared after achieving the equilibrium, the next question is what kind of soil profile has actually been achieved. In early days, water contents with depth were measured from soil samples taken from a centrifuge model on a laboratory floor after centrifuge operation, indirectly to obtain a strength profile of the model. Unconfined compressive strength was measured, and hand vane test was also conducted on the laboratory floor. Quality of the measured data was not convincing because of possible sucking water available in the model package during the period between centrifuge operation and lab-floor measurement.

Centrifuge modeler started developing in-flight devices to find out the soil strength with depth and even at several locations over the soil model. Various tools have been developed over the years since 1980s to identify a more accurate soil profile of the model in flight. The devices developed are fundamentally a miniature of tools used in the field. Devices used in centrifuge tests must be small enough, powerful enough and remote controllable.

Figure 12 is a chart of the development of devices used under centrifugal acceleration, showing separately for clay model (lower half) and for sand model (upper half).

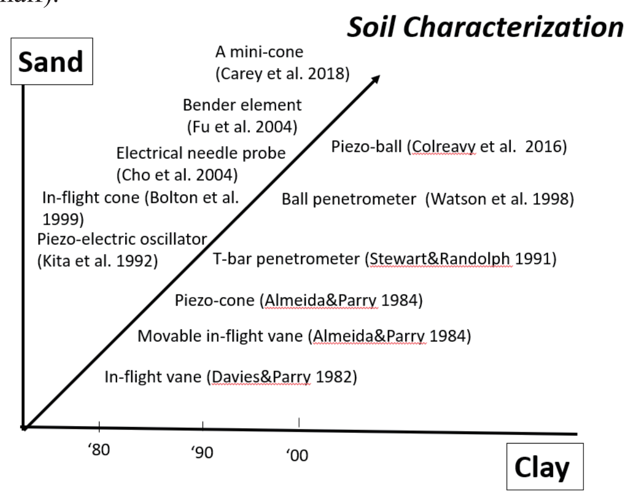

Fig. 12. Chart of development in soil characterization.

An in-flight vane apparatus was first developed by Davies and Parry (1982), to determine the strength of kaolin beds during flight. Almeida and Parry (1984) further developed the vane apparatus for the determination of the clay strength profile at different locations during the centrifuge tests. Almeida and Parry also developed penetrometer apparatus and piezocone.

The development was followed by T-bar penetrometer (Stewart and Randolph, 1991), ball penetrometer (Watson et al., 1998) and piezo ball (Colreavy et al., 2016). Presently, 'full-flow' penetrometer devices such as T-bar penetrometer and ball penetrometer are extensively used for soil characterization in geotechnical centrifuge clay models. The major advantage of "full-flow" penetrometers over the traditional cone penetrometer is that the flow of soil from the front to the back of the probe minimizes the need to correct for the overburden stress from the measured penetration resistance.

For sand model, Kita et al. (1992) developed a method of measuring the shear wave velocity of sand by using a piezo-electric oscillator and two accelerometers. Bender element was also used for measuring shear wave velocity (Fu et al., 2004). The use of in-flight cone was reported (Bolton et al., 1999) and Cho et al. (2004) described the use of electrical needle probe for soil spatial variability. More recently the development of a new mini cone was reported (Carey et al., 2018).

c) Modelling construction sequence

Modelling construction sequence remains a major area of research in centrifuge modelling. Soil behavior is highly dependent on stress path. Importance of modelling stress path changes during construction processes in the field was emphasized by Muir Wood (2004). In this note, two areas of development are reviewed, which are embankment (loading) and excavation (unloading), as is presented in Figure 13. Challenges are how accurately to replicate construction sequence in the field, which are needed to be remotely controlled in centrifuge.

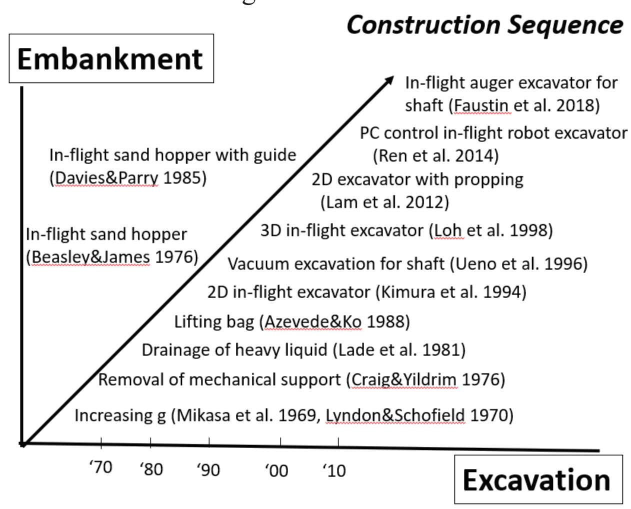

Fig. 13. Chart of development in modelling construction sequences.

(i) Embankment

The construction procedure of embankment in the field is typically to repeat several cycles of spreading a layer of soil and compacting each layer by a roller. It seems that no successful attempts are reported to model realistic embankment construction sequence. Currently the established experimental technique is to place a model embankment by raining dry sand in flight.

Before in-flight sand hopper was developed, modelling embankment construction on cohesive deposits was to prepare a foundation soil in a model container and then place a model of embankment over the foundation soil on the laboratory floor, then the container was subjected to increasing centrifuge acceleration to undrained failure ('speed up method').

More realistically simulating the construction of embankment is to replicate the construction process in centrifuge. The first attempt was made by Beasley and James (1976), in which a model bank is made of dry sand, and they poured from a hopper mounted on the model container; the gate of the hopper can be opened or closed at will by means of a pneumatically operated jack. The aperture at the base of the hopper is a slot, forming like an expanding 'heap'. An improved version was that it consists of a number of narrow hoppers side by side, the apertures at the base of which all operate simultaneously, to form a more realistic trapezoidal shape of embankment (Davies and Parry, 1985).

Since then, the situation remains after four decades without much development. No attempt has been made to clayey embankment. Craig (1995) described this situation as "*Many experimenters have simulated the placement of cohesionless fills by raining dry sand from storage hoppers mounted above a rotating model..... there remains much development before model fills experience the stress regimes associated with roller or vibratory compaction in the field. Cohesive materials present even more intractable difficulties.*"

(ii) Excavation processes

Modelling excavation processes are more complicated than modelling embankment construction. Embankment construction is to add additional body of materials on the existing model, whereas excavation is to remove a part of existing soil, which is associated with changes of stress and seepage boundaries.

A number of techniques have been developed to simulate the stress changes involved in excavation. In early days, a method of increasing centrifugal acceleration until failure was used for the stability of slope (Mikasa et al. 1969, Lyndon and Schofield, 1970.) The scale factor continually changes with the acceleration, and it is not possible to model the progressive movement owing to excavation in the field.

Removal of mechanical support was developed by Craig and Yildirim (1976), which is more realistic in modeling the stress history and is regarded as a pioneering work of subsequent development of modelling excavation. The concept was to control boundary stresses and deflection on an excavation of predetermined form. After performing a vertical excavation in a soil block, 4 vertical support plates are brought into contact with the soil face. These plates are locked in position while centrifuge accelerations are increased but can be withdrawn independently to simulate the removal of soil by excavation once the desired acceleration is reached.

Drainage of fluids ($Zncl_2$-solution and paraffin oil) was first used by Lade et al. (1981) for modelling deep vertical shaft in dry sand. $Zncl_2$-solutions can be made with densities from 1.9 g/cm^3 up to approximately 2.9 g/cm^3, thus including the range of possible densities for soil. Since then, this technique was widely used (Kusakabe, 1982, for axisymmetric excavation in clay, Bolton, M.D. and Powrie, W., 1987 for 2D excavation in clay) before the development of in -flight excavator. One of the drawbacks of this method is that the coefficient of lateral stress (Ko) is always one because of using a fluid. Other method such as lifting of bags or blocks of soil technique was reported by Azevede and Ko (1988) at the same period.

Since a small yet powerful stepping motor controlled by PC became available in 1990s, the next stage of development of replicating the excavation process emerged. An in-flight excavator was developed by Kimura et al, (1993, 1994) for 2D excavation and Loh et al. (1998) for 3D excavation. Lam et al. (2012) developed a new apparatus for modelling excavation processes with propping mechanism and reported the test results for 2D situation (Lam et al. 2014). Recently Ma and Xu (2018) adopted Lam's system for the study of excavations in Shanghai clay.

Ren et al. (2014) reported the development of four-axis robotic manipulator, controlling coordinates of x, y, z and rotational angle θ, which was applied to in-flight layered soil excavation.

Shaft excavation needs more sophisticated technique. Ueno et al. (1996) developed a vacuum excavation system to remove sand at the center of the shaft during the centrifuge test. To simulate an excavation, a negative pneumatic pressure was applied to the bottom of the perforated tube to draw sand from the center of the shaft to a collection point. For the vertical shaft excavation, in-flight shaft excavation system was developed by Faustin et al. (2018a). The system comprised three main features: a single flight auger, a two-axis servo-actuator and a mechanical device to remove the excavated clay from the auger after each excavation step. Faustin et al. (2018b) extended the system to excavate elliptical shafts.

It may be interesting to create a similar chart of construction sequences between piling (loading) and tunneling (unloading).

d) Modeling Earthquake

Figure 14 presents a chart of developments of experimental systems for modelling earthquake. The upper-half in the figure shows the pseudo-static systems and the dynamic systems in the lower-half of the figure.

Pseudo-static systems such as tilting mechanism and tilting table have been used mainly for stability of slopes, dams, and recently of reinforced retaining walls to observe the progress of deformation leading to failure mechanism, and to validate design methods with novel reinforced methods. In contrast, dynamic systems, predominantly servo-hydraulic actuator, are utilized to study of liquefaction, and soil-structure interaction to observe the mechanism of degradation due to cyclic shearing and to validate design methods with novel construction method.

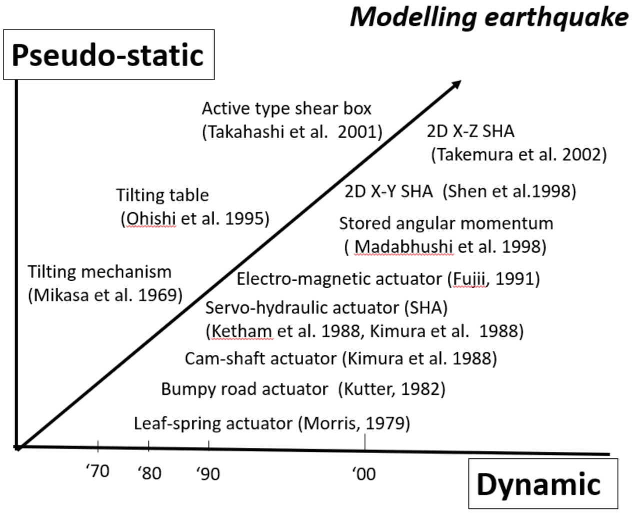

Fig. 14. Chart of development in modelling earthquake.

(i) Pseudo-static system

Seismic Coefficient Method

After the Great San Francisco in 1906, a Japanese engineer introduced a simple, yet practical design method, called Seismic Coefficient Method for aseismic design of buildings (Sano,1916). The concept of Seismic Coefficient Method is based on d' Alembert's principle in physics. The method was applied to geotechnical structures such as retaining wall, after the Great Kanto Earthquake in 1923. which caused casualty more than 100 thousand people and damaged a great number of structures. Okabe (1924) wrote in his paper that "*The writer has been, for many years, in charge of the design and the construction of quay walls at Yokohama Harbour and faced directly to the severe earthquake, which gave dreadful damage to the existing quay wall*". He proposed the earth pressure theory presently known as Mononobe-Okabe method, by extending Coulomb's limit equilibrium method of earth pressure theory, incorporating a horizontal component of the maximum acceleration due to earthquake. At the Kobe earthquake in 1995, a modified Mononobe-Okabe method was proposed for higher seismic loads (Koseki, et al.,1998).

Before the advent of modern computer, numerical solutions of dynamic equation were not readily available for geotechnical engineers. It was a natural consequence, therefore, that modelling earthquake in centrifuge started with a quasi-static system. When Mikasa and his colleagues at the Osaka City University developed their centrifuge in late 1960s (Mikasa et al.,1969), they designed a centrifuge machine with a tilting mechanism illustrated in Figure 15.

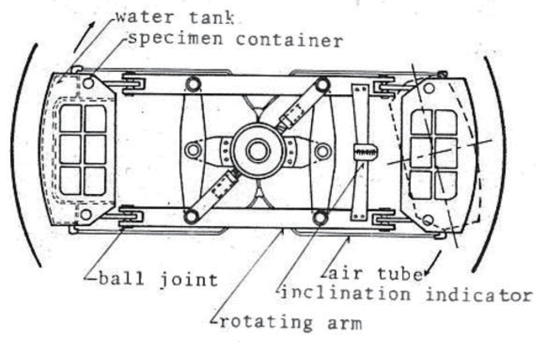

Fig. 15. Pseudo-static system (Mikasa et al. 1969).

The machine has two parallel arms, and model containers were hanged at the end of the arms by ball joints. The container can be inclined up to +/- 16.7 degrees during centrifuge operation at a fixed acceleration by parallel opposite movements of the arms driven by a motor located at the center, simulating quasi-static loading. The inclination was measured by the indicator indicated in the figure. They used the system for the study of stability of rock fill dams.

Taniguchi et al. (1988) at PWRI reported the experimental study of stability of reinforced embankments by non-woven fabric using the tilting mechanism and compared the test results with the circular slip surface analysis, incorporating the seismic coefficient method.

Ohishi et al. (1995) followed the line of quasi-static system, by developing a static tilting table for a centrifuge, as shown in Figure 16. The tilting table is mounted on the centrifuge. The table can be tilted up to 20 degrees.

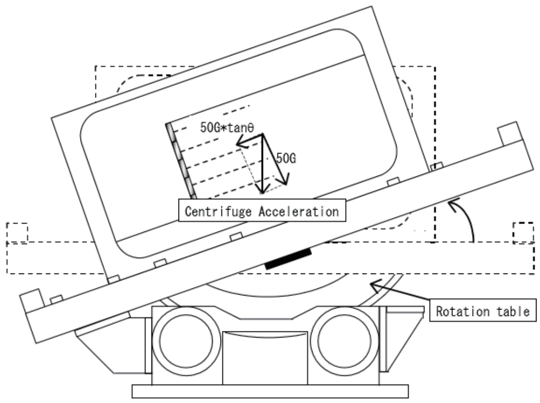

Fig. 16. Tilting table (Ohishi et al. 1995).

Since a technology of high-speed camera was not available until around 2000 (Okamura et al., 2001), the tilting test was occasionally used to capture the progress of deformation up to failure and to validate the stability analysis of limit equilibrium method used in the design.

The tilting table have subsequently been used for the study of geogrid reinforced embankment (Izawa et al., 2002, Izawa and Kuwano, 2010) and stability of slope reinforced by rock bolts with prestressed facing plate (Nakamoto et al., 2015). Reasons for adopting the tilting mechanism in the centrifuge testing is stemmed from the current design method for the reinforced wall which adopts the Seismic Coefficient Method.

Recently Hou (2018) reported the rotating container to study of toppling slopes, made of municipal solid waste, which is a similar facility to the tilting table developed by Ohishi et al. (1995).

Response displacement method

Based on the observation of dynamic behaviour of underground structures during earthquakes, it has become clear that the deformation of underground structures is governed by the shear deformation in the surrounding ground. Response displacement method has been developed and used in some design codes for underground structures such as gas pipelines, water supply buried pipes. The simplest of this type of method is a model of a beam on an elastic foundation.

Along the line with response displacement method, Takahashi et al. (2001) developed an active type of shear box for a study of pile due to lateral movement of soil during earthquake under quasi-static conditions, neglecting inertial effects of soils and pile. This shear box was later used for a study of a tunnel in sand subjected to shear deformation (Shibayama et al., 2010).

(ii) Dynamic system

The advent of advanced computer enables engineers to carry out dynamic analysis for non-linear system. Dynamic system for modelling earthquake in centrifuge has been developed over the years. Key supporting peripheral technologies for this development include servo-technology to create a realistic earthquake motion and high-speed camera technology to capture movements of the model during the dynamic excitation.

Development of dynamic actuator began by using an explosive charge and followed by a leaf-spring earthquake actuator (Morris, 1979). These methods are limited to create one dynamic event. Bumpy road earthquake actuator (Kutter, 1982) was developed, which is a mechanical system using a sinusoidal track constructed by the wall of the centrifuge pit. Stored Angular Momentum actuator was later developed (Madabhushi et al., 1998). Only one earthquake of fixed amplitude and duration was possible. These mechanical actuators produced only sinusoidal earthquake motions.

Servo-hydraulic actuator controlled by PC has become available in 1980s. Servo-hydraulic earthquake actuator (Ketcham et al.,1988, Kimura et al., 1988, Inatomi et al., 1988) have been used worldwide. Advantage of adopting the servo-hydraulic actuator controlled by PC is able to simulate realistic earthquake motions recorded by seismographs during previous earthquakes. Servo-hydraulic earthquake actuator for two-dimensional (2D) motion in x-y plane (Shen et al. 1998, Kim et al. 2006, Sasanakul et al. 2014), and 2D in x-z plane (Takemura et al. 2002, Hou et al. 2010) were developed later.

Actuator for drum centrifuge has also been developed by Kusakabe and Grung (1997), using a simple triangular cam mechanism, more recently by Miyamoto et al. (2018). The system developed by Miyamoto et al. (2018) enables them to study the model behaviour by a sequential action of earthquake and tsunami, which will be presented later.

Ohishi et al. (1995) reported that direct comparison of embankment behaviours in static tilting and shaking table tests. They found that since the tilting method imposes monotonically increasing horizonal component to the model until failure, a visible slip surface was formed, while the shaking table test imposed a number of cyclic shearing, resulting in soil element settling in the vertical direction. They did not observe the clear slip surface formation.

In connection with the modelling earthquake, it may be appropriate to touch on the development of fault simulator. Recent study on a fault simulator by Takemura et al. (2020) provides a useful table of previous model studies on fault including 1 g and Ng environments.

e) Modelling Ocean Wave

There were early works on modelling stability of slopes and dams due to draw-down (Avgherinos and Schofield 1969, Mikasa et al., 1969) and modelling seepage through soil structures (Padfield and Schofield, 1983) about four decades ago.

Modelling soil-water-structure interaction is a relatively new challenge in geotechnical engineering. Modelling soil-water-structure interaction certainly widens the scope of physical modelling in geotechnical engineering, including hydrodynamics events. In the context of global warming and rising sea water level, modelling soil-water interaction and modelling ocean wave becomes of vital importance particularly in issues of low land areas.

Intensive activities related to development of ocean spaces and oceanic resources trigged an attention to phenomenon of seabed responses by travelling ocean wave in 1970s (e.g., Henkel, 1970). Wave-induced liquefaction studies were carried out so far by theoretical analysis and cyclic triaxial torsional shear tests in laboratory (e.g., Ishihara and Yamazaki, 1983), by a series of model tests using a 2.1m high column one-dimensional wave loading apparatus in laboratory (Zen and Yamazaki, 1992), and by 1g model tests (Sumer et al., 1999).

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Detailed mechanisms of wave-induced liquefaction affecting pipelines or anchors in seabed can be observed by proper centrifuge modelling. A challenge is how to reproduce ocean wave in centrifuge. To eliminate the boundary effect imposed by model container in beam-type centrifuge, sufficiently large container is needed, or an effective reflective wave absorber is to be installed. Drum-type centrifuge, in contrast, has an advantage over beam-type centrifuge in this respect and can offer a long and endless water channel.

Figure 17 presents a chart of modelling ocean wave generation both for drum-type centrifuge and beam-type centrifuge.

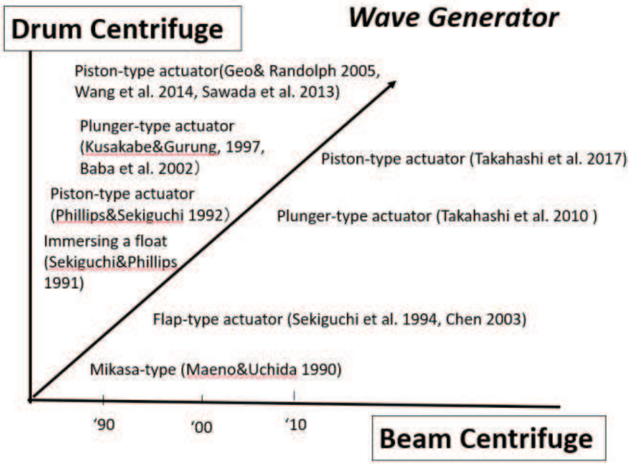


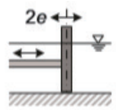
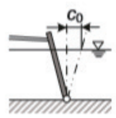
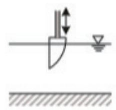
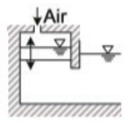
Fig. 17. Chart of development of wave generator.

Generation of ocean wave in a centrifuge requires a system in which wave can be generated in a control manner. Takahashi et al. (2019) presented a useful table for classification of a wave generator with mechanism as given in Table 1. Hereafter, this lecture note uses these terminologies.

As far as the author is aware of, Maeno and Uchida (1990) first attempted to generate wave-like pressure changes of water to study the pressure changes in a sand bed using the Mikasa-type centrifuge as was illustrated in Figure 15, by imposing a series of repetitive tilting motion of the whole model package during centrifuge operation. Occurrence of accumulation of residual pore pressure and densification of the sand bed were reported. It is the author's view, however, that the pioneer's work of generation of surface gravity wave in a centrifuge is the work by Sekiguchi and Phillips (1991).

Professor Schofield had an ingenious idea for a horizontally rotating drum centrifuge facility, in which there is a central column rotating independently from the rotation of the drum. All the necessarily equipment and apparatus can be mounted on the central column. The drum centrifuge was designed and installed at Schofield center. This is the starting point.

Table 1. Types of wave generator in centrifuge model (Takahashi et al. 2019).

Type	Schematic view	Mechanism
Piston		A vertical wave making plate reciprocates horizontally.
Flap		The top of a wave making plate reciprocates around the hinge at the bottom of a plate.
Quasi-flap		The hinge of the flap-type is embedded downward.
Plunger		A triangular or curved plunger reciprocates vertically.
Pressure		Air pressure in the chamber attached to a water channel fluctuates.

Sekiguchi and Phillips (1991) theoretically derived the dispersion relationship of surface gravity waves in the rotating drum, taking the Coriolis effects into consideration, and presented an approximate theory of wave-making by rapidly immersing a rectangular float in water. Experimental verification was conducted in the 2m diameter drum centrifuge at Cambridge University. Figure 18 illustrates the test arrangement in the drum centrifuge.

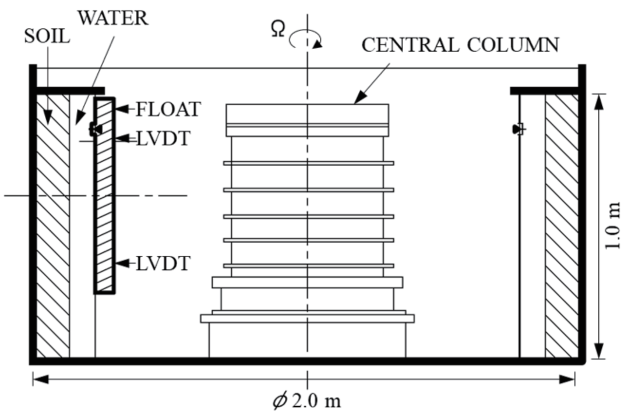


Fig. 18. Wave generator in a drum centrifuge (Sekiguchi and Phillips 1991).

Phillips and Sekiguchi (1992) further developed the system of piston-type actuator for wave trains. The system is depicted in Figure 19.

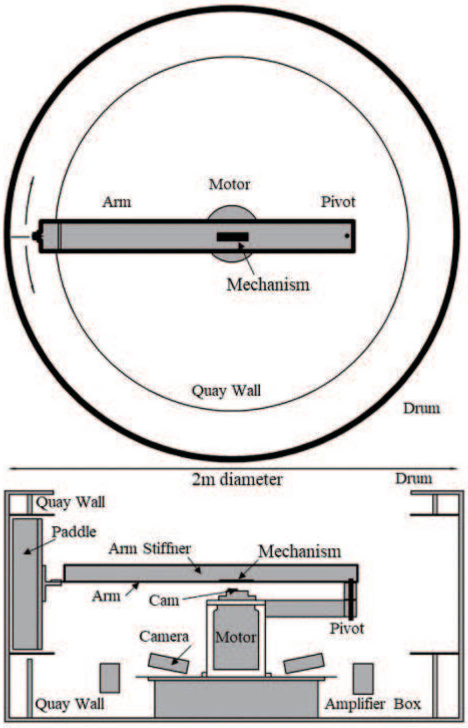


Fig. 19. Improved wave generator (Phillips and Sekiguchi 1992).

The actuator is driven from an electric motor which is mounted coaxially with the drum axis. The motor housing supports a reaction arm to which a pivot point is driven via an adjustable cam and scotch-yoke mechanism attached to the top of the drive motor. The paddle at the end of the arm is a close fit inside the wave channel. The actuator system developed can generate gravity waves at excitation of 6 to 25Hz for up to 100mm deep water under up to 150g.

Since drum centrifuge facility has a potential to provide a longer channel, efforts to develop a wave generator continued such as plunger-type actuator by Kusakabe and Gurung (1997), plunger-type actuator by Baba et al. (2002), piston-type actuator by Geo and Randolph (2005), piston-type generator (Sawada et al. 2013), piston-type actuator by Wang et al. (2014).

Professor Schofield provided Toyo construction a piece of advice on planning, designing, and installation of a 2.2 m diameter drum centrifuge. The Toyo drum centrifuge has 2.2 m in outer diameter, 6.7 m in circumference, 0.3 m deep and either 0.3 m or 0.8 m width and spins up to 440 g (Miyake et al., 2002). What follows is the development of wave generator of Toyo drum centrifuge.

Baba et al. (2002) developed a plunger-type wave generator. The case where a wave generator and a geotechnical model is positioned in an opposite side, corresponds to about a wave traveling length of 1.5 km long under 440 g, expecting to exhibit the characteristics of long wave. The wave generator first developed was a plunger-type with the capacity of creating a wave of 4.0 m high and a frequency of 5 sec. under 100 g. Figures 20 and 21 depict the whole test system of wave test system in the drum and the wave generator, respectively.

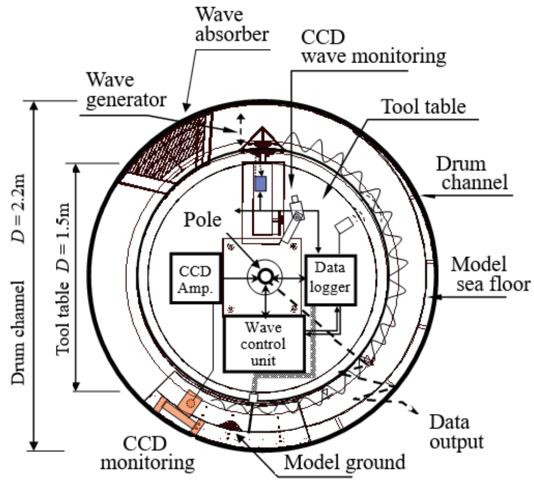


Fig. 20. Wave test system in Toyo drum centrifuge (Baba et al. 2002).

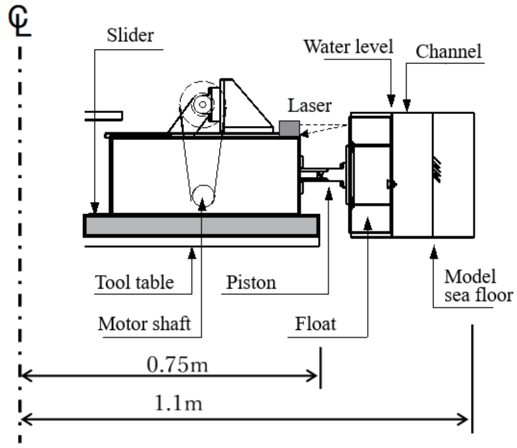


Fig. 21. Plunger-type wave generator in Toyo drum centrifuge (Baba et al. 2002).

Initial experimental results showed a good agreement with a numerical simulation, with respect to wave formation and corresponding pore pressure changes with time, demonstrating the usefulness of the wave generator in the drum centrifuge.

Since the plunger-type wave generator produces a regular wave with the fixed amplitude and frequnecy, the researchers at Toyo developed a piston-type wave generator (Sawada et al., 2013) and further developed a piston control system by installing an AC serbo-motor with a feedback system by a LDT (Miyamoto et al.,

2018) to produce a series of irregular waves, as is shown in Figure 22.

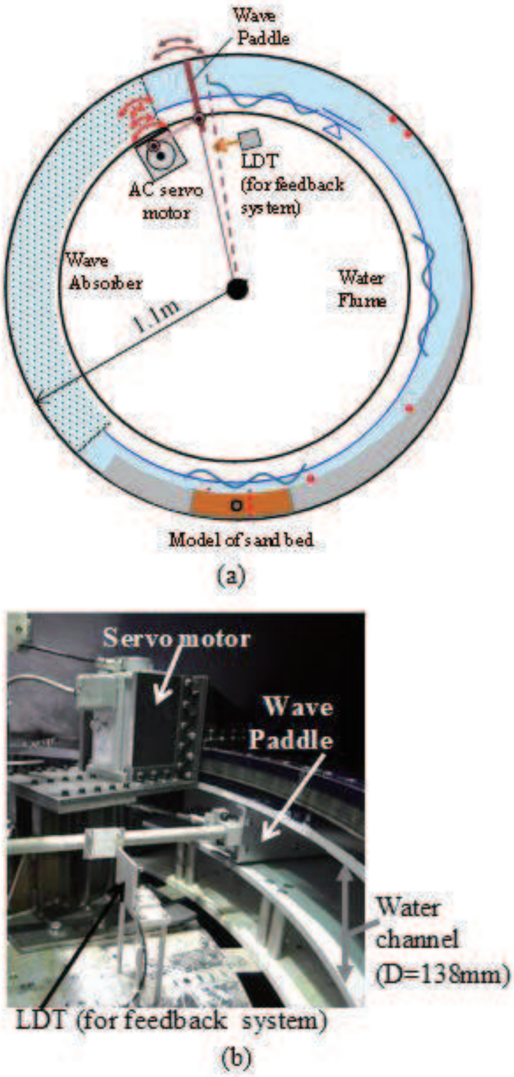
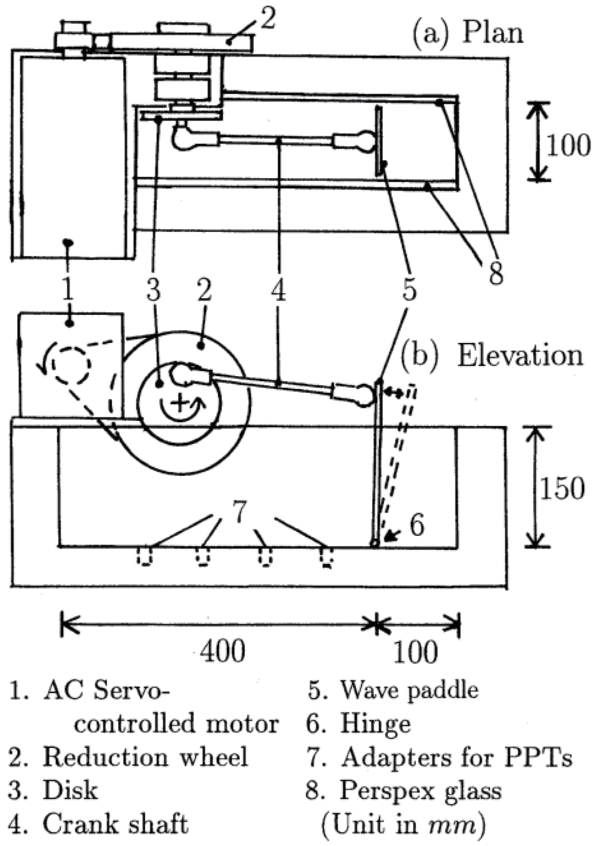


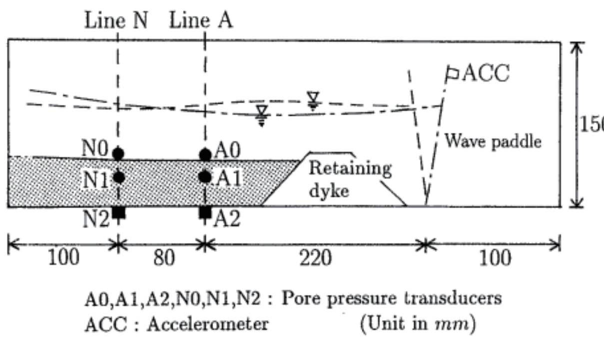
Fig. 22. Piston type wave generator with feedback systemin in Toyo drum centrifuge (Miyamoto et al. 2018).

With this system, Miyamoto et al. (2018) reported a series of centrifuge test results on wave-induced liquefaction and floatation of pile buried in sand beds. They observed that liquefaction zone propagated downwards in the course of wave loading, and the floatation of the buried pipe to the soil surface was a consequence of progressive liquefaction.

Let us to see, next, the development of wave generator in beam-type centrifuge. Sekiguchi et al. (1994) developed a wave generator of flap-type for the study of the liquefaction of sand bed due to standing wave for the verification of their closed form solution related to the wave-induced pore pressure changes in cohesionless deposits, as is presented in Figure 23, (a) wave generator, and (b) experimental setup.



(a) wav generator



(b) experimental setup

Fig. 23. Flap-type wave generator in Kyoto-Univ. beam centrifuge (Sekiguchi et al. 1994).

By installing a slotted partition at the opposite side of the container, Sekiguchi et al. (1995) modified the wave generator to generate progressive waves, as shown in Figure 24. Note that in this system they employed a quasi-flap-type generator which offers a higher efficiency of wave making than the flap type previously employed.

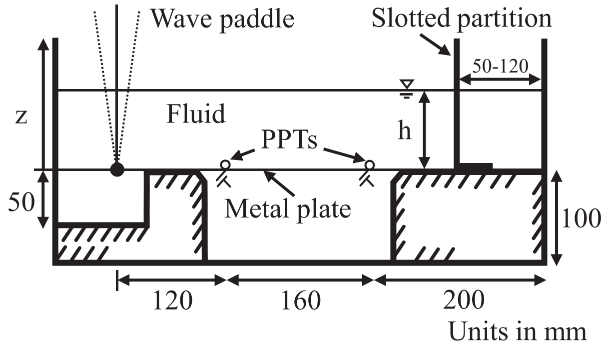


Fig. 24. Improved flap-type wave generator in Kyoto Univ. (Sekiguchi et al. 1995).

Chang (2003) described a flap-type wave generation with the similar concept to the original Sekiguchi's wave generator for the beam centrifuge at the National University of Singapore.

Sekiguchi firmly established the concept and methodology of wave generator in centrifuge, but the dimension of their container is restricted by the size of centrifuge. Larger centrifuge is required to further development for study of seashore or harbor structures subjected to wave action.

Port and Airport Research Institute (PARI) continued further development of wave generator. Takahashi et al. (2019) reported the detailed development of hydro-geotechnical beam centrifuge in PARI, including various water flow and wave generators. PARI centrifuge Mark II-R has an effective radius of 3.8 m, maximum payload 2.76 ton at 113 g. Dimensions of the platform are 1.7 m long x 1.6 m wide, on which long containers can be mounted.

PARI has followed three stages of development and improvements: from plunger-type, piston-type with cam mechanism to piston-type with a PC control hydraulic cylinder. First, they developed a plunger-type wave generator to study wave force resistance of artificial seashore reclaimed by granular treated soil (Takahashi et al., 2010).

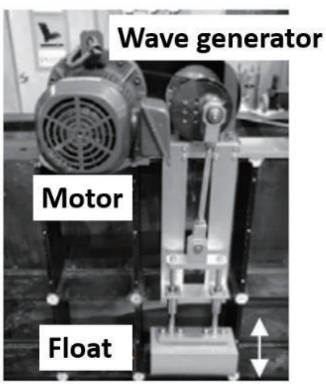


Fig. 25. Plunger-type wave generator at PARI.

Next development was piston-type wave generator with cam mechanism is given in Figure 26.

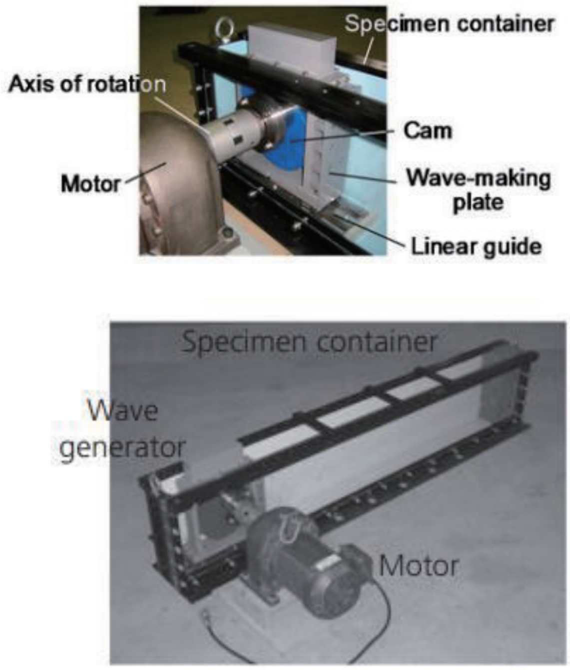
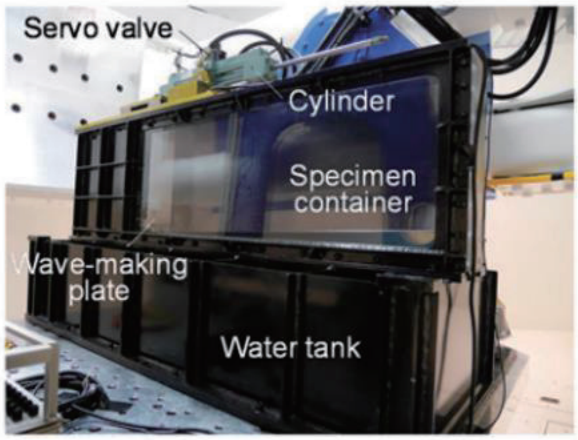


Fig. 26. Piston-type wave generator at PARI.

Cam mechanism can produce a series of regular wave with the same wave height and frequency. They used this system for modelling breaking waves and seashore ground (Takahashi et al., 2019), and stability of seawalls subjected to high waves (Takahashi and Morikawa, 2017).

For reproducing a more realistic irregular waves with irregular wave height and frequency, they further made improvement and adopted a piston-type with a PC control hydraulic cylinder, by which they can produce any type of irregular waves, as presented in Figure 27.



(a) Appearance

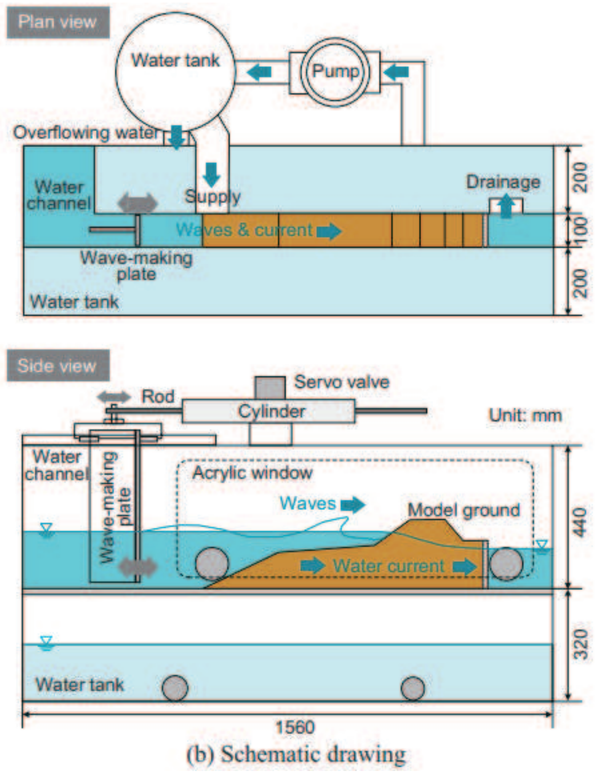


Fig. 27. Servo-controlled wave generator (Takahashi et al. 2019).

f) Modelling tsunami events

Scientists and engineers make progress in their understanding of natural phenomena, when facing unpreceded events such as natural disasters. An example of this is the Great East Japan Earthquake with a moment magnitude of M=9.0 occurred along a subduction zone in the Pacific Ocean on March 11, 2011. This earthquake triggered enormous tsunami disasters. The maximum height of over 21 m was recorded at Fukushima Prefecture.

The tsunami generates thrust forces generated from arriving waves acting on structures such as breakwaters, as well as a water level difference acting on the walls of the breakwaters between that at the seaward side and that at the landward side. The water level difference generates seepage flow and uplift forces in the rubble foundation, leading to piping and boiling near the breakwater, which was evident from the pictures during the tsunami event. This results in reducing the bearing capacity, leading to the failure of caisson type breakwater. Further increase in tsunami high generates the overflow, leading to further scouring in the rubble foundation. Field investigation after the tsunami accelerated the challenges for modelling tsunami event in a centrifuge.

Mechanism of tsunami differs from that of ocean wave previously described. Thus, there was a new challenge for modelling tsunami events. From physical modelling points of view, modelers may be interested in the following three points: (1) How to generate tsunami-like wave, (2) Verification of occurrence of turbulent flow, and (3) Development of possible countermeasures.

Modelling tsunami events requires a large amount of water to be rapidly supplied to the model system. As far as the author's knowledge there are some groups tackling modelling tsunami events, including PARI, Kyoto University, Toyo construction in Japan, and one group in the US where Exton et al. (2018) reported a challenge for developing a device to simulate tsunami loading.

Let us see the development in drum-type centrifuge, first. Toyo in fact began the development of Tsunami-like wave generator before the Great East Japan Earthquake in 2011, based on the accumulated experiences of ocean wave studies. Miyake et al. (2009) developed a tsunami generator of dam-break type as shown in Figure 28.

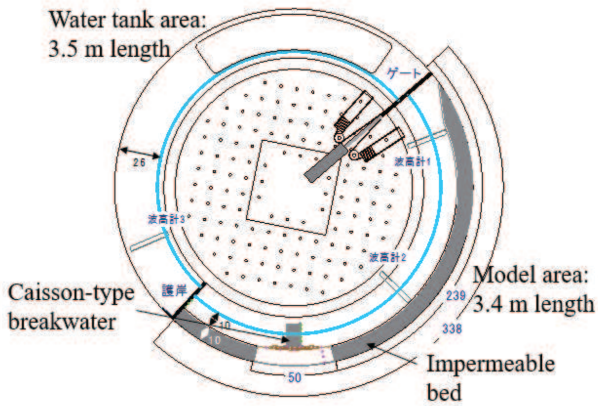


Fig. 28. Tsunami-like wave generator in Toyo drum centrifuge (Miyake et al. 2009).

The drum centrifuge channel is divided into two areas; a half of the channel is used for a reservoir (water tank area) and the other half for the model test area, in which a model breakwater is resting on a rubble mound above the layer of sand. In between there is a water gate which can open and close by operating an air cylinder mounted on a tool plate at the center of the drum, creating a tsunami of which height can be controlled by changing the water level difference between the reservoir and the mode area.

Proof test without model sand beds revealed that characteristics of the generated tsunami propagation is comparable to the theoretical prediction by a linear long wave theory, as well as the test results conducted in 1g in a large water channel test. Using this system, the tests were performed to observe a model caisson type breakwater experiencing the attack of a tsunami, measuring the water pressures on the caisson and the pore water pressures in the sand layer at various locations.

Since the drum rotates in a horizontal plane, a method for installing the model into the drum channel was a challenge. Thus, the whole model with the caisson was frozen before the centrifuge run. Results of centrifuge tests were compared with a numerical simulation (Imase et al., 2011, 2012).

With the first system of dam-break type, there was a limitation in height of tsunami due to insufficient amount of water available at the reservoir area (Miyamoto et al. 2014). The improvements were made: (1) the width of channel used was narrowed to a half of the reservoir zone, (2) the location of the gate was placed nearer to the model caisson to increase the reservoir area, and (3) installation of a drainage zone to lengthen the time of reflected wave to arrive the model, as is shown in Figure 29.

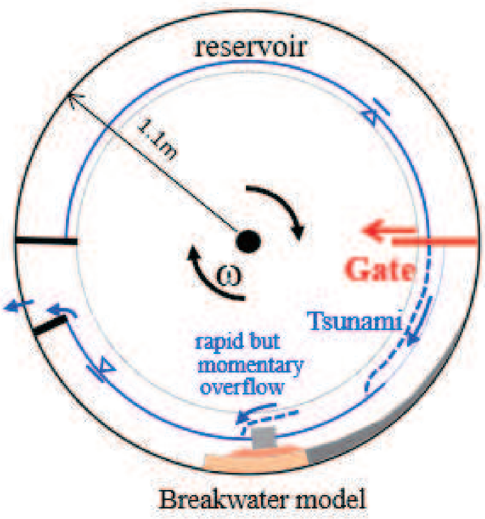


Fig. 29. Imporeved tsunami generator in Toyo drum centrifuge (Miyamoto et al. 2014).

With the improved tsunami generator, they successfully observed the process of instability of caisson associated with the instability of rubble mound. From which they confirmed the effectiveness of a proposed method to improve the stability of caisson by placing rubble at the back of the caisson. They studied the failure mechanism of composite breakwater brought by the instability of a foundation mound due to seepage flow induced by a tsunami, and observed the occurrence of boiling and fluidization. Later, the research group at Toyo developed a piston-type generator (Sawada et al. 2013) and a circulation system with a circulation pump for modelling prolong overflow event caused by a large earthquake shown in Figure 30 (Tsurugasaki et al., 2015).

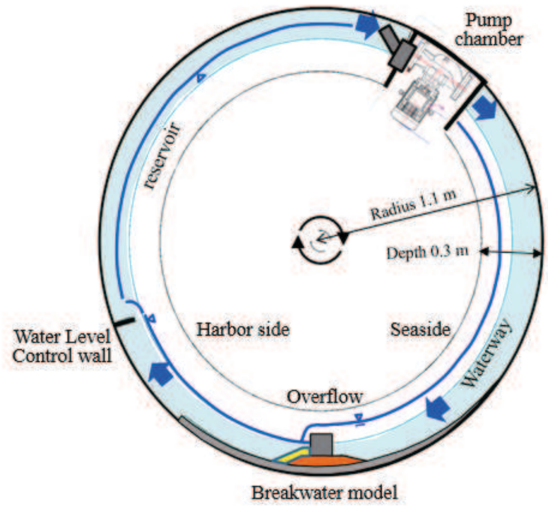
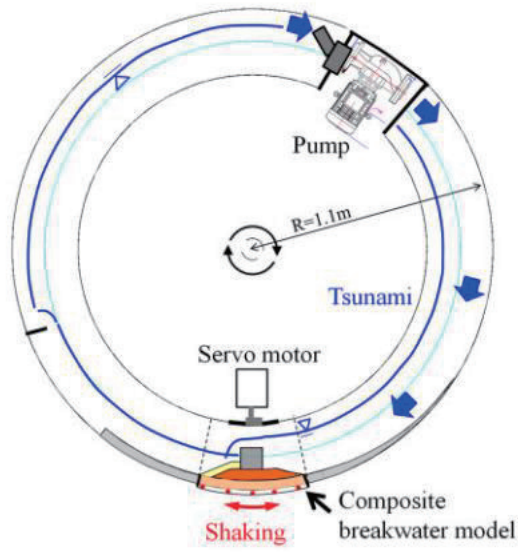
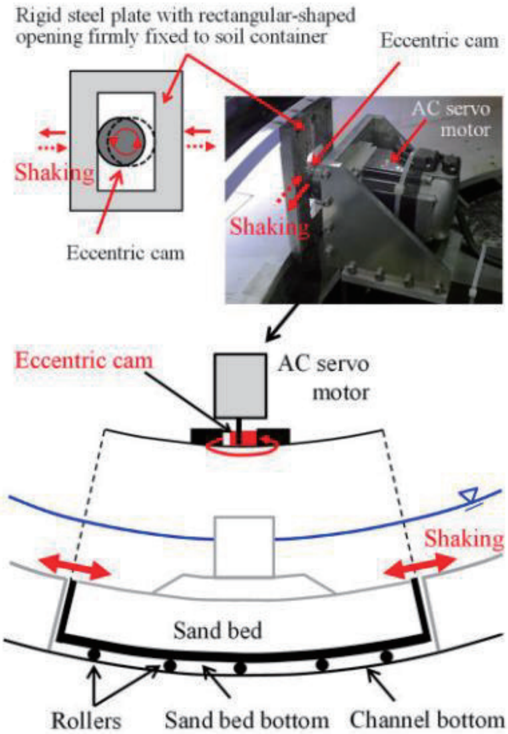


Fig. 30. Tsunami generator with a circulation pump in Toyo drum centrifuge (Tsurugasaki et al. 2015).

Combined with a shaking table system shown in Figure 31, Miyamoto et al. (2018) described a testing method for stability of breakwater foundation under combined actions of earthquake and tsunami. They examined two scenarios; one is that a tsunami comes after an earthquake, the other the simultaneous occurrence of earthquake and tsunami.



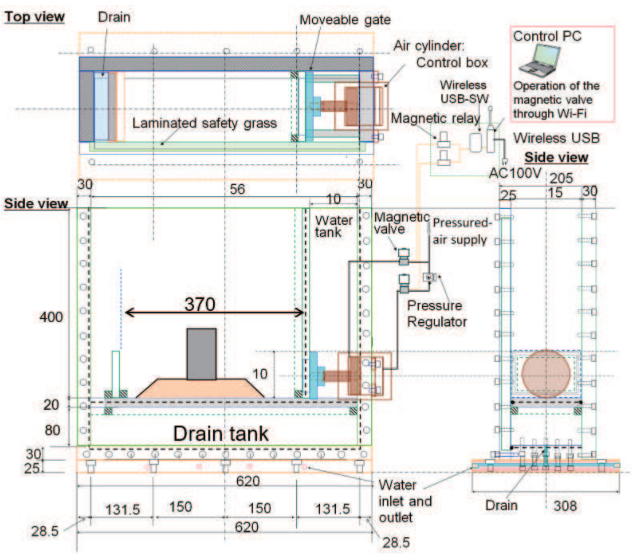
(a) test system



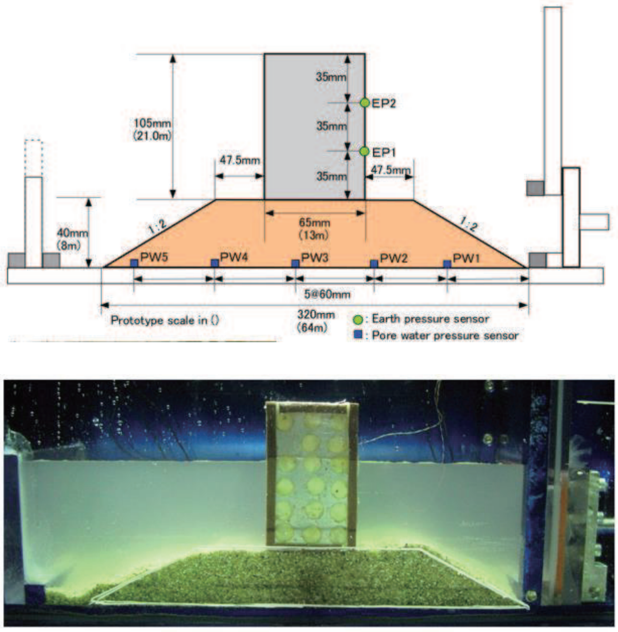
(b) shaking table mounted on drum

Fig. 31. Earthquake-tsunami generator at Toyo drum centrifuge (Miyamot et al. 2018).

Let us see the system developed in beam centrifuge, next. In Kyoto University, the centrifuge has an effective radius of 2.5 m and 24 g-ton capacity. The platform accommodates a model container with maximum dimensions of 620 mm wide and 480 mm high. The tsunami-like wave generator developed by Tobita and Iai (2014), as is shown in Figure 32.



(a) test system



(b) model caisson and rubble mound

Fig. 32. Test system and model caisson and rubble mound in Kyoto Univ. beam centrifuge (Tobita and Iai 2014).

The model container is relatively small, 620 mm wide and 400 mm high, in which the whole model system must be contained. There is a water reservoir at the side of the container and a drainage tank at the bottom, leaving a limited space for a model of caisson (105 mm high and 65 mm wide) resting on a rubble mound (40 mm high and 320 mm wide). The tsunami like-wave is generated by opening a horizontally removable gate controlled by a PC operating a movement of bellofram cylinder. Once the water is released from the water reservoir, it flows across the soil box where the model structure is placed. There is a vertical plate on the opposite side of the gate which controls the initial water depth prior to tsunami event and allow the excess water overflowing into the drainage tank to prevent a reflected wave from being generated by the plate.

In scaling prototype model into a reduced scale model, it is inevitable to use a high acceleration. Generating tsunami-like wave used is so-called dam-break system, and the duration of the event is governed by a capacity of the reservoir. They used this system to study damage mechanisms of a breakwater and of a building with piled foundation (Tobita and Iai, 2014).

At PARI, Takahashi et al. (2013a, 2013b, 2014) developed a dam-break type system of modelling tsunami events as shown in Figure 33.

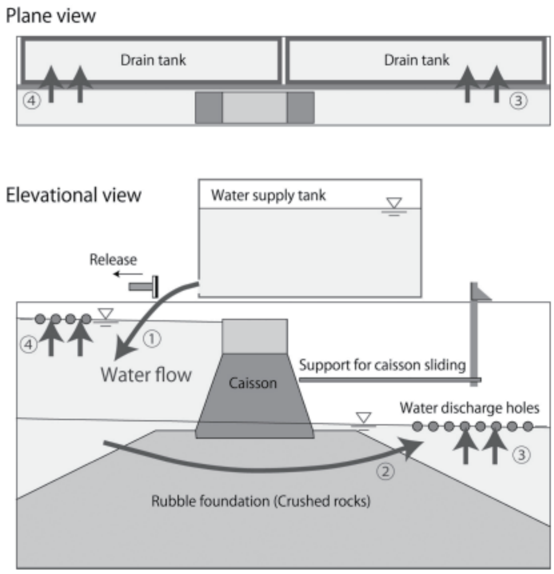
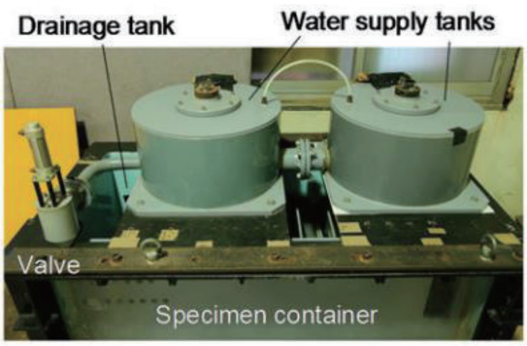


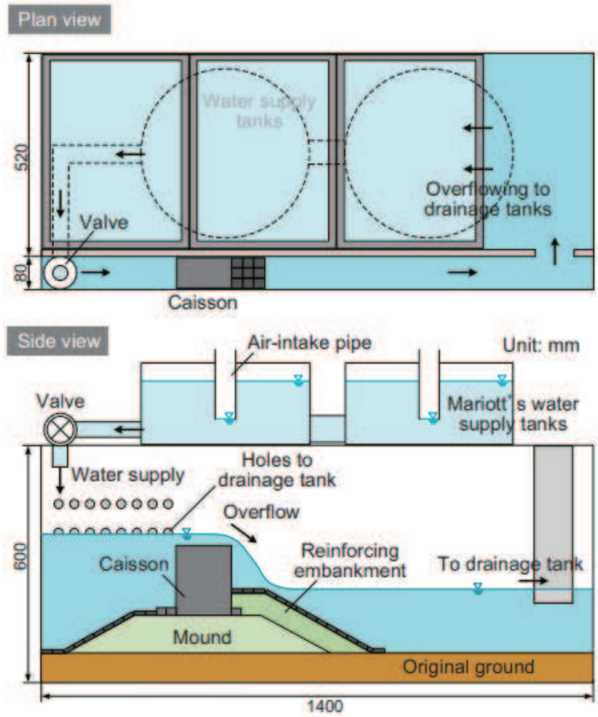
Fig. 33. Dam-break type tsunami generator at PARI (Takahashi et al. 2014).

There is a water supply tank mounted on the model container. Since proper control of the flow volume and/or the water level is not easy in dam-break type systems, a series of water discharge holes are made in the back wall of the model container to control the water levels. The excess water through the holes is collected in two tanks installed behind the back wall. With this system, they confirmed the occurrence of turbulence flow seeping through a model breakwater foundation mound and observed the occurrence of boiling. By using this system, they also conducted a series of horizontal loading tests, investigate the decrease of bearing capacity due to seepage flow created by tsunami.

To modelling a combined effect of seepage and overflow, Takahashi et al. (2015) manufactured another system for water supply system, modelling a tsunami event which prolongs for a certain period, as is shown in Figure 34.



(a) Appearance



(b) Schematic drawing

Fig. 34. Water supply system at PARI (Takahashi et al. 2017).

The system has two tanks on the top of the model container, by which the amount of supplied water can maintain constant because the tank installs Marriott's pipes. With this system, they conducted tsunami induced overflow-seepage-couple experiments for studying mound score and also examined the effectiveness of reinforcing embankment as a countermeasure.

g) Summary

We have overviewed the historical developments in the six selected topics. The historical development in the former three topics, model preparation, soil characterization, and modelling construction sequence, is a history of development unique to geotechnical engineering. It appears that a proper understanding of fundamental knowledge of soil mechanics and characteristics of geotechnical projects in construction practice has formed a basis for pushing the modelling development forward. Efforts over a half century have provided us a well-established, useful set of modelling techniques and modelling apparatus, although there remain many challenges such as modelling structured soil.

In contrast, for the latter three topics, modelling earthquake, modelling ocean wave, and modelling tsunami events, it is apparent that advance in peripheral technology, such as mechatronics, robotics, and computer technology, largely have largely contributed to the development of physical modelling and the expansion of application field. It is therefore, anticipated that further innovative development may be achieved by introducing cutting edge technology into the field of geotechnical physical modelling, such as 3D printer technology (Liang et al., 2017). The future of physical modelling may be beyond my imagination.

4 SCALING ISSUES

The principles of similitude remain as a central issue in the centrifuge modelling. Schofield (1980), Taylor (1994), Muir Wood (2004), Towhata (2007), and more recently, Madabhushi (2015) describes the similitudes in the centrifuge modelling. As part of TC activities, Garnier et al. (2007) compiled catalogues of scaling laws and similitude questions in geotechnical centrifuge modelling for a wide range of physical events. Takahashi et al. (2017) presented scaling laws including soil-flow interaction. Every time we challenge a new boundary value problem in a reduced model, scaling laws must be examined.

In this note, recent two scaling issues will be discussed which are "generalized scaling laws" and "spatial variability".

a) Generalized scaling laws

A series of papers related to "Generalized scaling laws" has been recently presented. The concept of two-stage scaling was proposed by Iai et al. (2005). They mentioned that the motivation of this concept was stemmed from the trend toward physical modelling of larger prototypes during dynamic situations. In this proposed method, a prototype is scaled down in two stages. In the first stage, a prototype is scaled down into "an intermediate virtual model" based on the scaling laws in a 1g field with a scaling factor of μ. In the second stage this model is further scale down into a physical model using the conventional scaling relations in the centrifuge field with a scaling factor of η. In this manner, a large scaling factor $\lambda=\mu\ \eta$ can be broken down into the scaling factor μ and η.

Scaling laws in 1 g field are based on the work by Iai (1989). He assumed for constitutive law of soil that the stress-strain relation is determined irrespective of the confining pressure if appropriate scaling factors are introduced. For this purpose, he used tests results of plane strain compression on saturated Toyoura sand by Tatsuoka et al. (1986) and presented the normalized stress ratios– normalized axial strain curves, by selecting a scaling factor for axial strain at stress ratio of 4.

Iai wrote that the assumption is applicable within the intermediate strain levels, up to about 10 %; i.e., the strain levels which are lower than at strains at failure. And he concluded that the similitude derived in his study is applicable to the model tests in which the major concern is directed toward the deformation, rather than the ultimate state of stability, of the soil-structure-fluid system.

Tobita et al. (2011) examined the applicability of the generalized scaling laws to saturated ground by conducting a series of dynamic test following the concept of 'modelling of models', with four combinations of the scaling factor μ and η. They concluded that the scaling of acceleration and excess pore-water pressure were confirmed, but the scaling of the ground settlement could not be properly evaluated.

Tobita et al. (2014) further discussed the applicability of the generalized scaling laws for fundamental physical properties, and Tobita and Iai (2014) extended the generalized scaling laws for the study of failure mechanism. More recently, Sawada et al. (2018) examined the applicability of the generalized scaling laws to pile-inclined ground system, Borghei and Ghayoomi (2018) evaluated the two-stage scaling in modelling soil-foundation-structure systems, and Kim and Jo (2018) also examined the two-stage modelling of dams for seismic performance evaluation.

The concept of two-stage modelling drew considerable attention among centrifuge modelers and a collaborative study was conducted on the applications and limitations of the concept. Among them, Takemura and Takeuchi (2019) examined the generalized scaling laws by conducting two sets of modelling of models on laterally loaded large diameter single piles in sand. The model piles were subjected to monotonically increasing horizontal loads in a static condition. They concluded that the generalized scaling laws could be applicable at small pile top displacement, e.g., 1 % pile diameter, but beyond yielding, the resistance tends to be underestimated as μ increases especially for relatively stiff pile.

b) Spatial variability

In the geotechnical design, it has been a common practice to model the soil profile at a site deduced from the results of site investigation and laboratory testing into a simplified system for design, consisting of homogeneous layers with constant soil properties within a layer, neglecting the fluctuation of these soil properties.

Capability of computer exponential increases with time in a manner of Moore's law, which makes Monte Carlo simulation possible in design practice as a routine work, previously considered practically impossible.

There has been a tendency that nature of design code is shifting from deterministic approach to probabilistic approach, reflecting ISO 2394: General Principles on Reliability for Structures (1998), which adopted reliability-base design. Statistical database of geotechnical parameters (e.g., Phoon and Kulhaway, 1999) is available, not exclusively though, together with accumulated knowledge of reliability theory and probability analysis in geotechnical field.

From mid-1990s, specialists in reliability analysis started critically examining centrifuge test results (e.g., Popescu and Provost, 1995). How has this tendency influenced on physical modelling community?

It has been a fundamental attitude of physical modelers traditionally that they prepare soil models as uniform and repeatable as possible to enable them to carry out a parametric study in a consistent manner. Even so, physical modelers know that variation of the results of model tests does exist in sandy model, such as model density (Ueno, 2000) and cone penetration resistances (Bolton et al., 1999), considered mainly due to modelling method and devises used at different research institutions.

In recent years there has been many papers discussing accuracy/error of centrifuge test data. There is an argument (Zhang et al. 2008, Zhang and Zhang, 2014) that scale of fluctuation should be modeled as part of scaling requirements, that is to say, the following equation should be hold,

$$\delta_{model}/\delta_{prototype} = 1/N$$

where δ is the scale of fluctuation, and δ_{model} and $\delta_{prototype}$ is the scale of fluctuation in model and protype, respectively and N is a geometrical scaling number.

The scale of fluctuation(δ) was first introduced by Vanmarcke (1977) in geotechnical field, which measures *"the distance within which the soil property shows relatively strong correlation or persistence from point to point"*.

According to Vanmarcke (1977), three parameters are needed to describe the spatial variation of soil profile characteristic that is treated as random: namely the mean, the standard deviation or the dimensionless coefficient of variation, and the scale of fluctuation. The scale of fluctuation can be related to autocorrelation distance when a type of auto-correlation function is given.

Two questions immediately arise about scaling requirements for the scale of fluctuation between prototype and reduced model.

Question 1: How could accurately the scale of fluctuation be measured or estimated in prototype?

Question 2: How could the scale of fluctuation be experimentally reproduced in a reduced model in a consistent manner?

Zhang et al. (2008) investigated the variability of soil properties in two centrifuge models and found that the coefficient of variation (COV) in centrifuge model is much smaller than that of field. Zhang and Zhang (2014) noted that centrifuge models are not completely homogeneous and do not possess the same statistical characteristics. Since the scale of fluctional does not change as model level, they will be scaled up to larger prototype scale of fluctuation, as the scaling ratio increases. To achieve similitude between model and prototype, they argued that statistical properties such as the coefficient of variation or the scale of fluctuation should be modeled as part of scaling requirements. They argued that the spatial soil variability is a necessary scaling law for centrifuge modeling but gave any answer to Question 2, leaving it for further research.

Garzon et al. (2014, 2015) presented an experimental technique to prepare two dimensional reduced-scale clay mode with controlled spatial variability. The similar method for preparing heterogeneous clay was also adopted by Jamshidi Chenari et al. (2018) for the study of consolidation properties of heterogeneous soil samples. The method proposed by Garzon et al. (2014, 2015) is as follows: The two-dimensional physical soil model consists of discrete cells which are a squared cell of equally sized. Each cell is analytically given a specific number ranging from 1 to 9 by using a discrete random field generation method. Separately they prepared nine 'homogenous' soils obtained by mixing different percentages of kaolin and bentonite. The soil columns of these nine 'homogenous' soils are placed to match the analytical model to create a 'heterogenous' soil model. Subsequently Garzon et al. (2018) carried out a series of loading tests of stirp footing resting on the heterogenous soil. Due to the author's limited knowledge, it is not clear that this method is in fact able to answer Question 2.

Spatial variation is truly 3D nature. Pau et al. (2018) presented the development of a 3D clay printer that allows the construction of physical heterogenous model. The 3 D printer can work with eight types of reconstituted clay soil.

As was overviewed earlier, one of the key driving forces of these developments is the attitude of researchers to proper modelling of the target phenomenon. Proper modelling means not necessarily to precisely reproduce every aspect involved in the phenomenon, but to reproduce essential elements of the phenomenon by simplification, scrutinizing what is important and what is less important.

It is the author's present view that the evaluation of the real value of research on spatial variation of reduced model may remain a subject for further discussion.

5 LARGE-SCALE MODEL TEST IN GRAVITATIONAL FIELD

There is a classical discussion on which is more reliable and useful, full-scale test vs. model test, in-situ test vs. laboratory test, large-scale 1g test vs. centrifuge test. Schofield (2000) wrote that *"Terzaghi strongly criticized all papers on small scale physical modelling as 'papers whose authors do not hesitate to generalize the conclusions derived from pure theory or from small scale tests on materials with very little if any resemblance to real soils'. He stated that 'One of the* *principal goals of instruction in soil mechanics should be to discourage this prevailing tendency to unwarranted generalization'. He went on to speak of 'the utter futility of the attempts to discover any single-valued relation between the results of small-scale loading tests and of the settlement of large foundation on stratified soils*.

As was quoted earlier, Roscoe (1970) stated that "*The centrifuge will provide much reliable evidence but can never fully replace a properly instrumented full-scale field test",* while Schofield' view (2000) was that *"Centrifuge tests now solve problems where observation at full scale is no help*."

Which view is closer to your own view? Terzaghi? Roscoe? or Schofield?

Physical modelling includes a model test conducted under earth gravity environment. In recent years, large scale model tests in gravitational field have been carried out mostly in the area of shaking table test.

Einde et al. (2004) described an outdoor large shaking table (12.2 m x 7.6 m). Tokimatsu and Suzuki (2009) reported shaking table tests on soil-pile-structure interaction using a laminar shear box, of which dimensions are 4.6 or 6.1 m in height, 12.0 m in width and 3.5 m in length. Suzuki et al. (2014) examined factors affecting stress distribution of a 3x3 pile group in a cylindrical laminar box with a height of 6.5 m and an inner diameter of 8.0 m. Motamed et al. (2010) conducted a series of large shaking table tests on pile group using a large square container of 1.95 m wide, 1.95 m long and 0.6 m high. Thevanaygam et al. (2018) developed a large rectangular laminar box of 2.74 m wide, 5.0 m long and 6.10 m high.

5.1 Large-scale model testing facilities in Japan

Some centrifuge modelers may share with the view that "*Large-scale models are resource and time consuming to conduct, which can lead to a lack of control over boundary conditions. In addition, in fine-grained soils, the time taken for pore pressure to build and equilibrate can render the test length excessive*." "*Close control over material properties and well-defined boundary conditions in physical models enable repeatability that permits parametric studies to be conducted*" (Davies et al., 2010).

Japan is prone to natural disasters, including slope failure caused by rainfall, various serious damages caused by earthquake and hightide/tsunami. In order to understand phenomena of natural disaster and to develop countermeasures, intensive site investigation has been made after occurrences of disasters every time. However, site investigation on site alone is not sufficient to deepen our understanding and to develop effective countermeasures. Man-made experimental facilities are required, by which detailed observation can be made and effectiveness of countermeasures can be examined. Physical modelling related to natural disasters is of vital importance.

There are three major governmental research institutions in Japan, which are National Research Institute for Earth Science and Disaster Resilience (NIED), Public Works Research Institute (PWRI), and Port and Airport Research Institute (PARI).

NIED and PWRI have a large-scale rainfall facility, by which disaster related to slope failure caused by heavy rainfall can be studied. The specifications of these facilities are given in Table 2.

Table 2. Specifications of large rainfall facility.

	NIED	PWRI
Rainfall conditions		
Area of rainfall	44m x 72m	20m x 19m
Rainfall intensity	15 – 30mm/h	10 – 100 mm/h
Diameter of raindrops	0.1 – 6mm	
Drop height of raindrops	16 m	

There exist a number of research works for modelling rainfall events in centrifuge with the development of in-flight rainfall simulator (e.g., Kimura et al., 1991, Tamate et al., 2012, Bhattacherjee and Viswanaddham, 2017). To modelling a realistic rainfall event in a reduced model, intensity, and duration of precipitation, falling velocity of rain droplets and impact pressure on the ground surface must be close enough to reality (Tamate et al., 2012).

Caicedo et al. (2015) pointed out that rainfall simulation in centrifuge is a challenging and difficult task, because the presence of Coriolis force, drag force, evaporation and wind within the centrifuge may affect the distribution of rainfall over the model. By developing a mathematical model, they concluded the followings: (1) The trajectories of rain droplets are affected by the Coriolis force, (2) Some portion of the small droplets never reach the surface of the model, thus the volume of water affecting the model differs from the volume of water projected by the nozzle. (3) The droplets' impact velocity depends on acceleration level and centrifuge geometry. The impact angle is not necessarily vertical.

Quite recently, centrifugal modeling of root reinforced soil slopes under rainfall condition was reported (Likitlersuang et al., 2017).

For earthquake related disaster study, NIED has a three-dimensional full-scale earthquake testing facility, commonly called "E-defense". PWRI also has a large facility. The specifications of these facilities are given in Table 3.

Table 3. Specifications of large shaking table.

	NIED	PWRI
Size of table	20m x 15m	8m x 8m
Model mass	1200t	300t
Earthquake conditions		
Direction of motion	X, Y, Z	X, Y, Z
Acceleration (Max.)		
horizontal	900 cm/s^2	+/- 2G
vertical	1500 cm/s^2	+/- 1G
Velocity (Max.)		
horizontal	200 cm/s	+/- 200 cm/s
vertical	70 cm/s	+/- 100 cm/s
Displacement (Max.)		
horizontal	+/- 100 cm	+/- 60 cm
vertical	+/- 50 cm	+/- 30 cm
Frequency		Up to 50 Hz

Port and Airport Research Institute (PAPI) has a large-scale open channel through which observation of model seabed can be made associated with wave motion. The channel has a length of 185 m, a width of 3.5 m and a depth of 12 m. At the bottom of the channel there is a four-meter-thick sand layer. The facility creates 3.5 m high wind-generated wave and 2.5 m high tsunami. The facility has been used for research on mitigation and restoration of storm and surge water disasters as well as of tsunami disasters.

5.2 Large model tests in 1g - advantages and disadvantages

E-defense has a policy of free access of experimental data. One of the interesting tests is about the effectiveness of seismic reinforcement for wooden house. An existing two story old wooden house was dismantled and re-constructed on one half of the shaking table by an experienced carpenter. On the other half of the shaking table, the identical two-story wooden house was built with seismic reinforcement. These two houses were subjected to the same shaking motion and see what happened. The direct comparison could be made. Obviously, the house without reinforcement collapsed first. The house with reinforcement survived against larger shaking motion. The video provides persuasive evidence and appeals to public. Certainly, model tests which are large enough close to real structure scale, have an advantage. Interpretation of the results requires no sophisticated similitude. In fact, housing industry often uses E- defense for demonstrating the seismic safety of their detached house. How about geotechnical physical modelling, using a reduced model based on a set of science-based similitude?

The limitations of centrifuge modeling using a reduced scale model has been discussed (Taylor, 1995). Let us first consider what advantages in 1g test are, referring to Tani (2014).

a) Do not need a centrifuge facility with a well experienced modeler. A large amount of initial investment is required for centrifuge facility and a long period of time is required for fostering a group of centrifuge modelers.

b) Model in the gravitational field is stational. The gravitational field is uniform throughout the model, whereas centrifugal field in the model is changing with radius and angle measured relative to the center of rotation. Throughout the processes from model preparation and conducting test, modelers can safely access to the model. Model systems and test procedures are free from various restrictions owing to remote-control system that centrifuge test requires. For model system and measurement devices, commercially available devices can be used.

c) Larger model container can be used compared to centrifuge container. The dimension of container is limited by the facility. Model container in 1 g test can be several times larger than those in centrifuge test. Larger model needs a smaller reduction ratio to prototype scale, implying that it is free from excessive simplification and idealization. Larger model can have a room for densely installed measurement devices, which provides a large set of measured data for understanding the model behaviour.

In contrast, the disadvantages are

a) Do not satisfy stress similitude.

b) It requires a longer model preparation time. Specially for large model using fine material, like clay. Consolidation time becomes excessive, and practically impossible to perform. Thus, large model tests conducted so far use sandy soils.

c) If model test in 1 g field is not large enough, low stress level associated with model size poses a difficulty in measuring pore water pressure and earth pressures in a reliable level.

d) Since the model preparation needs a longer period of time, a number of tests to be conducted is limited, resulting in difficulty in confirming repeatability of test and in improving test systems and procedures. It is also difficult for modelers to learn the experimental technique. To increase the number of tests also requires a substantial cost and time.

6 SUMMARY AND CONCLUDING REMARKS

History of science and engineering is a history of human intellectual activities. Further significant step forward in any discipline of science and engineering must be soundly based on the accumulated knowledge created by the wisdom of predecessors.

This lecture note has reviewed the role of physical modelling from various spectrums and has depicted the historical development in selected topics over a half century. What can we learn from them?

In the discussion of the role of physical modelling in industry, a unique feature of the role of physical modelling in Japan has emerged. Different from academia-industry relations in other countries, Japanese major contractors own their research center, which is equipped with a large geotechnical centrifuge facility, utilizing centrifuge model tests for consulting and supporting their actual construction projects, in addition to receiving research contracts from universities or other research institutions. It is a noteworthy fact from a point of view of social implementation of a technology.

Overview of historical development in the six selected topics was presented. The historical development in the former three topics, model preparation, soil characterization, and modelling construction sequence, is a development history unique to geotechnical engineering. It appears that a proper understanding of fundamental knowledge of soil mechanics and complexity of geotechnical projects in construction practice has formed a basis for pushing the modelling development forward. Efforts over a half century have provided us a well-established, and useful set of modelling techniques and modelling apparatus, although there remain many challenges for further scrutinization, such as modelling structured soil.

In contrast, for the latter three topics, modelling earthquake, modeling ocean wave, and modelling tsunami events, it is apparent that advance in peripheral technology has greatly contributed to the development of physical modelling and the expansion of application field. It is, therefore, anticipated in the future that further innovative development is likely to continue by introducing and implementing cutting edge technology into the field of geotechnical physical modelling.

Centrifuge model test is conducted under an accelerated centrifugal field. Scientific knowledge related to scaling law is required to properly understand the test results. In contrast, large-scale model test is conducted under the gravitational field. There exist several large-scale model test facilities in Japan which are often used for study of natural disaster. By looking these large-scale model tests under 1 g environment, some centrifuge modelers may criticize them as waste of time and money. It may be correct in some respect. But the question here we need to ask ourselves is that why decision-makers investigate huge expenses for constructing and operating these large facilities. What are advantages and disadvantages, when compared to the same amount of investment for centrifuge model testing? One of the key issues is, probably, social acceptability rather than scientific rationality. Test results of large-scale model test under 1 g environment may be easier to understand and more convincing to the majority of taxpayer, without understanding complex scientific knowledge of similarity laws. This indicates that centrifuge modelling community needs more efforts on outreach activities.

Technologies and techniques of physical modelling has rapidly developed and expanded application fields over these 50 years. At present time, it has become reasonably feasible to conduct a centrifuge model test to examine the complex phenomena of soil-water-structure interaction under combined actions of earthquake and tsunami. One of the key driving forces of these developments is the attitude of researchers to proper modelling of the target phenomenon. Proper modelling means not necessarily to precisely reproduce every aspect involved in the phenomenon in question, but to reproduce essential elements of the phenomenon by simplification through the process of scrutinizing what is important and what is less important. Simplification is a core of success of physical modelling.

No doubt physical modelling continues to further sophistication owing to the development of peripheral technology. Model test system continues to further complexity by implementing advanced cutting-edge technology. This may end up that manipulation of model test and data analysis are carried out in a sort of black box manner. Which may hinder a modeler to carefully observe the test results to find out something new. An exciting part of physical modelling is to discover an unexpected phenomenon (Bolton, 2014).

Finally, a few observations during the preparation of the note. It seems that some papers are lack of proper review and lack of necessary information. Development of science is based on the accumulated past knowledge. A method developed a half century ago is still being used as an established technique. This fact demonstrates the indispensable importance of proper and thorough review of previous research works. Scientific research paper must include sufficient information which enables other researchers to conduct the identical test for double-check the result. Detailed description of stress history is vital for clay model. Relative density alone is not sufficient information for sand model. Process of formation of soil fabric, process of saturation, amount of swing-up settlement should be properly described in the paper. This effort enables us to correctly share information among our community.

Science of physical modelling in geotechnical engineering may have already entered in the period of maturity. Research community and application field has increasingly expanded, and research papers have been accumulated. It is almost practically impossible for an induvial to overview the accumulated knowledge. It is an important task for TC104 to provide a guidance to beginners of physical modelling for continuity of our modelling community.

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