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Braced excavations and shafts

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ABSTRACT: This General Report reviews 31 papers submitted to the session on Braced Excavations and Shafts, which contain case records, detailed monitoring data, proposals for design, and large scale project descriptions.

1 INTRODUCTION

Following up the First Symposium on Underground Construction in Soft Ground at New Delhi in 1994, the Second Symposium at London attracted 31 papers related to braced excavations and shafts from the countries listed in Table 1. There were 26 papers on braced excavations and 5 papers on shafts. It was rather a surprise that there were no contributions from North America and some European countries. Thus the papers presented in the session may not cover a fully world-wide prospective but certainly contain new and valuable information about current underground construction practice in soft ground.

Table 1. Papers submitted to the Symposium

	Braced excavation	Shafts
Austria	1	
Brazil	1	
Japan	11	4
Netherlands	1	
Poland	1	
Singapore	1	
Russia	1	1
UK	9	

2 BRACED EXCAVATIONS

There have been 26 papers related to braced excavations covering a wide variety of topics, which may be classified into six groups as follows:

1) Failure or near failure case record and failure mechanism
2) Detailed monitoring design
3) Proposals for design
4) Use of FEM analysis
5) Project descriptions
6) Miscellaneous topics

2.1 *Failure or near failure case records and failure mechanism*

There are six papers classified into this category. Two papers describe cases of complete wall failure, and three papers report excessive deformations of either wall or the bottom of excavation, or both. There is one paper dealing with a laboratory model test, examining failure mechanism of braced wall system due to partial horizontal loading.

The paper by Maffei et al. describes a failure of a multi tied-back retaining wall, which occurred in 1985 during the excavation of a Sao Paulo Metro station constructed in a residual soil. The excavation of 12m deep and 140m long was executed by the cut-and-cover method. The retaining wall failed locally in an extension of 13m, in a semicircle failure surface with a radius of 5m, as is shown in Fig. 1.

A close examination of possible causes for the failure found that there was a seepage from a nearby electricity box which was full of water. The authors describe the scenario of the failure as "the harmful effect of the water seepage through the residual soil increases the wall pressure by means of following mechanism: the excavation relieved the confining stress in the soil causing a reduction of strength in an unfavourable geometry fracture originated from the parent rock. The water seepage decreases the resistance, causing considerable increases in wall pressure". The lessons to be learned here are (a) to use rigid system to retain residual soils and (b) wall displacement must be as small as possible to prevent the decrease in strength through unfavourable joints.

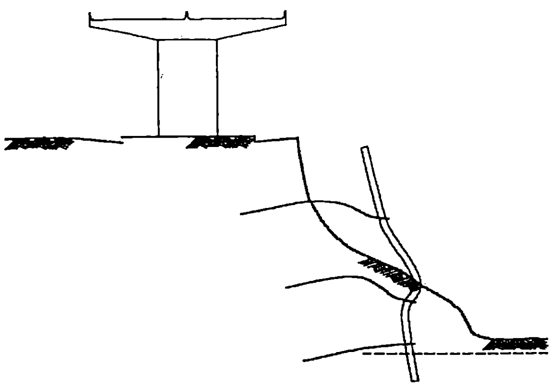


Figure 1. Section after failure. (Maffei et al.)

The paper by Toyosawa et al. reports a failure of a temporary earth support with H steel piles and lateral wooden sheeting, which occurred at an excavation of 17.7m wide and 30.3m long. Obvious cause for the wall failure was excessive excavation depth, some 3m deeper than the originally designed excavation depth of 11.4m.

Figure 2 illustrates estimated failure mechanism. This insufficient penetrating depth lost the bottom fixity of the piles and caused the inward movement of the piles, leading to a complete toppling failure of eleven piles, killing five workers. The paper demonstrates how important fundamental construction control is for safety.

Three papers from Japan report cases of excessive wall deformation and large heave at the bottom of excavation in a very soft alluvial clay near Tokyo. The alluvial clay is so weak that excavations often require soil improvement methods such as CJM (Column Jet Grout method), DJM (Dry Jet Mixing method) to provide sufficient passive resistance at the bottom of excavated side.

The paper by Ueki et al. and the paper by Nakagawa et al. describe these soil improvement methods in the project of Tokyo Bay Route of Metropolitan Expressway. From their experiences of using contact arrangement of improved soil columns (Fig. 3a), both papers point out that overlapped arrangement of the improved columns (Fig. 3b) is of essence to have reliable passive resistance.

In an excavation project of 45m wide, 66m long, and 20m deep supported by steel pipe sheet piles, Nakagawa et al. observed a lateral wall displacement of 80mm at the improved base soil, twice the design value, and significantly smaller values of coefficient of horizontal subgrade reaction, as small as less than 15% of the design value.

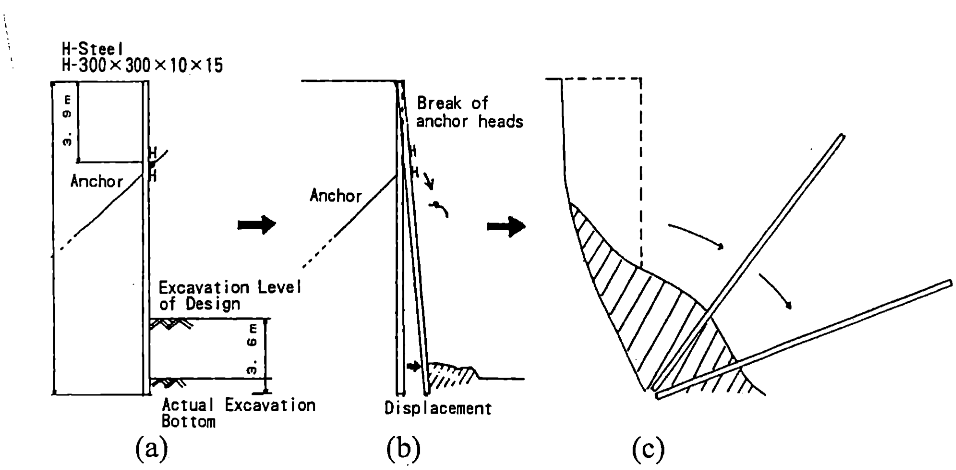
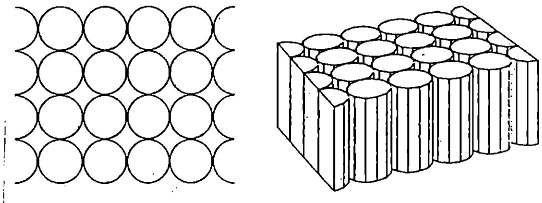
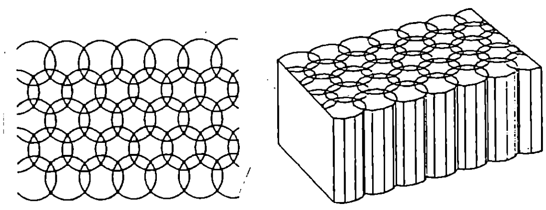


Figure 2. Estimated failure mechanism
(Toyosawa et al.)



a) contact arrangement



b) overlapped arrangement

Figure 3. Improved soil columns (Nakagawa et al.)

Large deformations of wall and a large amount of heave were reported by the paper of Tanaka in the project of Expansion of the Tokyo International Airport (Haneda) and also the paper by Ueki et al., which resulted in stop of excavation with fear of collapse of the retaining wall. Tanaka observed in his excavation project of 34.75m wide, 11.0m deep supported by steel sheet piles, that wall displacement and heave were as much as 300mm and 160mm respectively. Ueki et al. recorded 225mm heave. The measures taken then were the removal of the soil at the retained side together with dewatering by deep well (Tanaka), and the combination of the removal of the soil and water injection into the excavated area (Ueki et al.). Tanaka reckoned that the large deformation was caused by insufficient passive pressure at excavated side and examined an appropriate selection of shear strength at the excavated side, by scrutinising the possible factors affecting the shear strength, such as adhesion between the wall and the soil, anisotropy of strength, strength reduction due to swelling, progressive failure, strain rate and confining condition by a comprehensive laboratory test program. He finally concluded that the triaxial extension test provide a reasonable strength to be used in Rankine's formula for the passive earth pressure.

Expansive or highly overconsolidated cohesive layers beneath the excavation base are a potential source of swelling forces, which needs additional design considerations. The paper by de Boer and van der Eem gives an example of swelling forces on piles and walls, and the paper by Nash et al. provides detailed monitoring data of swelling behaviour of Gault clay in Cambridge, an expansive soil. The paper by Bolt et al. presents a series of model tests in the laboratory, studying an influence of an expansive or overconsolidated layer which might create partial horizontal forces on the wall. The model tests used Taylor-Schneebel's analogue soil, which is a mixture of two alloy rods having different diameters of 3 and 5mm. The horizontal pressure was modelled by a bag pressure. The conditions considered were number of strut and location of additional pressure relative to the retaining wall. Interesting failure modes are given in their paper.

2.2 Detailed monitoring data

Two papers present detailed monitoring data, which would facilitate our understanding of behaviour of the bottom of the excavation .

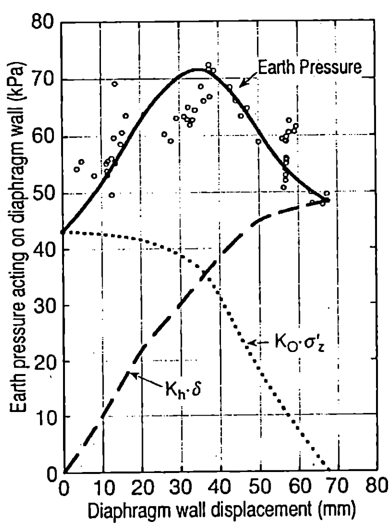


Figure 4. Change in earth pressure with diaphragm wall displacement (Tamano et al.)

Tamano et al. report an extensive monitoring of both total pressure and water pressure on a braced wall on excavated side, enabling them to separate the effective earth pressure and pore water pressure on the wall. The two sites monitored were excavations in soft clay for a sewerage pumping station in Osaka, of which c_u increases linearly with depth. The excavation depths were some 20m deep. The authors have a view that change in effective earth pressure is governed by two factors; removal of earth load by excavation and the wall displacement. The removal of earth load results in a decrease in total vertical pressure and water pressure, and consequently, lateral effective earth pressure drastically decreases with the progress of excavation, although K_0 value slightly increases with increasing OCR. On the other hand, the wall movement toward the excavated side creates an increase in lateral earth pressure and positive pore water pressure. Relative magnitude of these two factors controls the earth pressure change with wall displacement, as is shown in Fig. 4, where the earth pressure increases up to wall displacement of 30-45mm and decreases thereafter.

Nash et al. offer long term monitoring data of heaving and swelling of Gault clay beneath the base of excavation in the period of 1989 to 1995. The total movement amounts to around 110mm of which three quarters has developed since the end of construction in 1990, as is seen in Fig. 5. Field swelling index was found to be two to five times smaller than that obtained from oedometer test results.

2.3 *Proposals for design*

Design method develops from five reasons in most cases; from the lessons of failure, from experimental and numeral studies leading to new concept or design chart, from accumulated past experiences as a database, from new construction techniques including machinery, and from the introduction of new construction materials. There are four papers

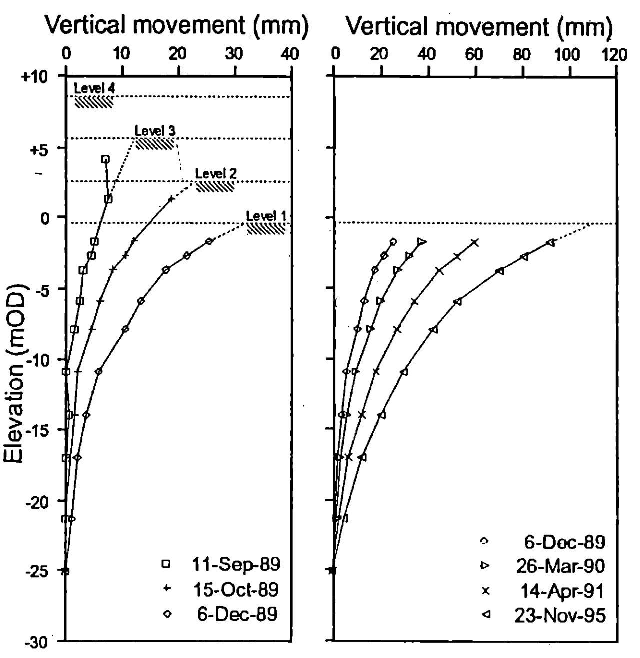


Figure 5 Vertical movements at various stages (Nash et al.)

which can be classified into this category.

The paper by Tanaka et al. proposes a method for calculating stability against boiling of sand within cofferdam, using "Prismatic failure concept" which states that safety factors for various prisms in the soil are calculated. The critical prism is determined by the condition that the safety factor is minimum along all of the prism. This method can be readily applicable to anisotropy or multi-layered soils, which is normally not considered in the conventional Terzaghi's method.

Chang and Wong propose a new apparent pressure diagram for braced excavations in soft clay with diaphragm wall. From their experience in the excavation in Taipei, they found that Terzaghi-Peck's apparent pressure diagram tends to underestimate the strut forces when $E_i/c_u < 500$ and $c_u^*/\gamma H<1.5$. They performed a set of FEM calculations using a hyperbolic non-linear stress-strain model in the undrained, total stress analysis and propose a new apparent pressure diagram as is given in Fig. 6.

There are two papers relating to database. Masuda complied 52 case records of maximum lateral deflection of concrete diaphragm walls in deep excavation (10-42m) by open cut method and deduced the correlation by taking into consideration of factors of soil properties, dimensions of diaphragm wall, spacing and number of struts and construction method. A similar database was collected by Fernie and Suckling to assess US semi-empirical approaches to lateral wall movement predictions for propped wall in a UK context covering stiff soils like London clay.

2.4 *Use of FEM analysis*

Environmental requirements impose strict

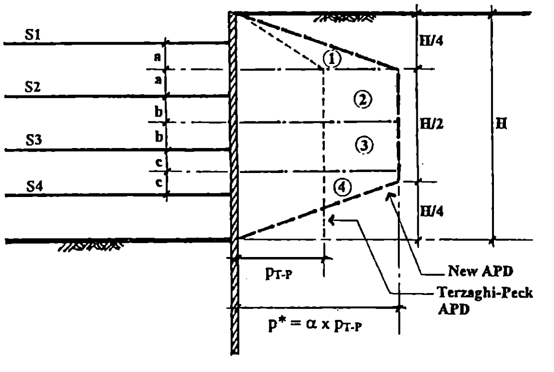


Figure 6. Amended apparent pressure diagram (Chang and Wong)

restrictions on ground deformation and movement of existing surrounding structures. To meet these requirements continuum mechanics approach such as FEM is necessary. FEM computer codes have recently been extensively used in underground construction design, both in two dimensional and three dimensional conditions. In most cases, reported FEM results show promising agreement with observations.

When plastic deformation is involved in the analysis, the detailed construction sequence must be properly modelled. The paper by Nakai et al. demonstrates the importance of proper modelling of the construction sequence, which affects the ground surface settlement and earth pressure distribution on wall, even when the final wall deflection is identical. They also pointed out the importance of friction between the wall and soil, that is to say, the settlement and the wall deflection decrease with increasing wall friction. Four papers by Breymann et al., de Boer and van der Eem, De Moor and Stevenson and Fernie et al. equally describe the capability of recent computer code, incorporating detailed modelling of construction sequences. Figure 7 shows an example of construction event modelled in the analysis.

Detailed modelling of construction sequence often involves the modelling of concrete; hydration and shrinkage process of cast concrete in the short term and creep behaviour of concrete in the long term, which has a significant effect, as was pointed out by De Moor and Stevenson. Equally important questions, when A-type prediction is to be attempted, are how to select input soil parameters, how to determine precise drainage conditions, how to determine in situ stresses prior to the excavation, and how to evaluate quantitatively the influence of disturbance caused by construction activities on the soil behaviour. In reality, however, the level of sophistication of analysis and site investigation is traditionally widely apart. Site investigation is often not adequate and sometimes there are no alternatives for design engineers to use limited information thus obtained to select the necessary soil parameters in the analysis. Nevertheless A-type prediction in some cases gives good agreement with the observation, as was the case described in the paper by Fernie et al.

From the comprehensive back analysis using CRISP program, De Moor and Stevenson found that the best fit between observed behaviour and back analysis was for analysis which incorporated reduced soil stresses and high soil stiffness.

Stage No.	Construction Event
1	Install diaphragm wall (wished into place)
2	Excavation to +1.3 m OD
3	Installation of temporary top prop at +2.0 m OD (top of wall +3.0 m OD); load of 50 kN/m applied to wall as prop pre-stress
4	Dewater Thames Gravel and excavate to -3.5 m OD (roof slab formation) dissipation pwps for three weeks
5	Install roof slab leaving small gap between slab and wall. Apply pressure loading over depth of roof slab to represent thermal expansion of concrete
6	Remove thermal expansion pressure
7	Infill wall/roof slab gap
8	Excavate beneath roof slab to -7.5 m OD
9	Excavate to -10.5 m OD
10	Install temporary mid prop at -9.5 m OD; load of 200 kN/m applied to wall as prop pre-stress
11	Excavate to -12.5 to -13.9 m OD (base slab formation). Dissipate pwps for three weeks
12	Install base slab (pin connection to wall)
13	Remove temporary mid prop
14	Dissipation of pwps - 16 weeks
15	Construct central wall and remove central piles below base slab
16	Dissipation of pwps - 33 weeks
17	Backfill on roof slab; change roof/wall connection from fixed to pinned
18	Restore original groundwater levels

Figure 7 Summary of construction events modelled in analysis (De Moor and Stevenson)

2.5 *Project descriptions*

One of exciting experiences often obtained from international gatherings is to hear new projects, including ongoing or forthcoming projects. There are six papers, mainly introducing design consideration, construction and monitoring in their large scale project. From UK there are four reports about Jubilee Line Extension project; two about Westminster Station by Carter et al. and by Crawley and Stones and one about Bermondsey Station by Dawson et al.. There is also a paper about Canada Water station (Batten et al.) with special reference to temperature measurements on prop loads. An exciting project is found in the paper by de Boer and van der Eem about a forthcoming project of Amsterdam Central Station as part of 9km underground line construction. Resin et al. report an on-going Manezhnaya Square Project in Moscow which is the construction of underground complex of 380m x 150m square, which is scheduled to be completed in September, 1997.

These project reports clearly demonstrate strict restrictions of underground construction in a congested urban site. Often imposed are the requirement to keep existing transport facilities operational as much as possible (for example, two existing underground lines in Westminster station), the requirement to ensure the safety of adjacent buildings, in particular, historical buildings (for example, clock tower containing Big Ben in the Westminster station, and 100 years old Amsterdam Central Station), and the requirement not to disturb the existing ground water regime (Manezhnaya Square). Also recent underground structures have an increasing trend of having a large open space (Westminster station). These strict restrictions inevitably lead to the detailed site investigations, intensive laboratory soil testing, sophisticated numerical predictions, and the adoption of observational method with extensive monitoring, as were described in the papers.

2.6 *Miscellaneous topics*

Four papers do not fall into any group. Horiuchi and Shimizu. report damage of wooden houses caused by a 300m long, 7m wide and 6.5m deep excavation for placing a underground drainage pipeline of 4.7m diameter. Only at the areas where there are wooden houses right behind the excavation line, stiff prefabricated pile wall columns were constructed, whereas conventional sheet pile walls were installed for the rest. In spite of relatively shallow depth of the excavation, considerable damage was reported. The damage zone extended to 60m from the excavation wall. This wide damage zone would suggest that damage zone extends not in two dimensional way but in three dimensional way and thus the sheet pile walls might not provide adequate support to prevent the ground movement. It is always true to say, as the authors stress, that the excavation should be shallower and the excavation duration should be shorter to minimise the damage to adjacent structures.

Gourvenec et al. present observation of diaphragm wall movements in Lias Clay during construction of the A4/A46 Bypass in Bath. They used earth berms as a temporary method of diaphragm wall support in place of temporary steel props and proved its effectiveness in supporting the walls with retained height of up to 9m. The observed wall movement was in the range of 20-40mm, which may be compared with prediction of approximately 30mm. They also observed that 30-50% of wall movement occurred during the excavation of the berm, implying the importance of support at the base.

Saji and Numakami propose a new composite earth retaining wall consisting of soil cement and RC concrete underground wall connected by stud bolts to control displacement of retaining wall when struts are released. A case record of monitoring 27m deep excavation using this composite earth retaining wall in soft clay is also reported. The proposed design method, using a two dimensional elastic spring model was verified by good agreement between the prediction and the observation.

As a continuation of their work presented at New Delhi Symposium, Ishida et al. report two case histories of field applications of their newly developed earth pressure device. It seems that further development will continue before reaching the authors final targets to use their device as part of an information control system.

3 SHAFT

There are five papers related to shaft; four papers from Japan and one from Russia. The paper by Abe and Muramatsu presents statistical data about 24 large-scale vertical shafts recently constructed in Japan, summarising their dimensions, wall displacements and surrounding ground deformations. The paper shows (1) the largest excavation depth is as deep as 80m, and the largest diameter as large as 80m, (2) the wall lengths are in the range of 1.4-1.7 times excavation depth, (3) the wall thickness generally increases with the wall length, (4) the maximum lateral wall displacements are less than 25mm for cylindrical shaft, regardless of the scale, whereas in some rectangular shafts the wall lateral movement is as large as over 200mm, (5) the surface settlement is less than 0.5% of excavation depth. The paper also reports a case history of a cylindrical shaft of 28.2m in diameter, 98m in depth constructed by diaphragm wall. The measured lateral wall pressure is lower than the conventional two dimensional Rankine's active earth pressure. The authors inferred that the reasons are stemmed partly from three dimensional effect and partly from the assumption of cohesion of a stiff sand layer being zero. Deformation mode predicted was that the wall deformation increases with increasing depth, whereas the actual measured was completely reverse; the wall deformation decreases with depth. The observation may suggest that the design method needs further modifications, or the accuracy of measurement should be improved.

The paper by Enami et al. presents a case history of an open caisson of 30.4m diameter and 36m depth constructed through a sand layer having SPT N value = 10-40, measuring peripheral friction as well as wall pressure. The data presented provide valuable information about the sinking mechanism of open caisson. Two important observations were made; one is that peripheral friction is considerably larger than design criterion, which may also be a matter of concern from the view of bearing capacity of caisson foundation, and the other is that the lateral wall pressure is different from one predicted by the two dimensional earth pressure theory. These two papers pose a need for fundamental studies on (1) pressure distribution on shaft wall, (2) influence of shaft stiffness on wall pressure and (3) influence of cross sectional geometry on wall pressure.

The paper by Fujii et al. report centrifuge test results of pressure distribution on rigid cylindrical shaft in dry sand. They show, as is seen in Fig. 8, that measured pressure is much smaller than the conventional two dimensional prediction and is close to the prediction by Berezantzev (1958) up to the two-thirds of the excavation depth, and the pressure at further down again increases with depth towards the bottom of the excavation. The distribution had a similarity with the data presented by Enami et al. in the caisson construction and was also confirmed by three dimensional FEM predictions employing an elastoplastic model.

In their centrifuge tests Ueno et al. also examine the pressure distribution of shaft wall with special reference to the effect of shaft stiffness. They used a newly developed vacuum excavator in flight, closely simulating the excavation process. They came up with a design proposal for earth pressure,

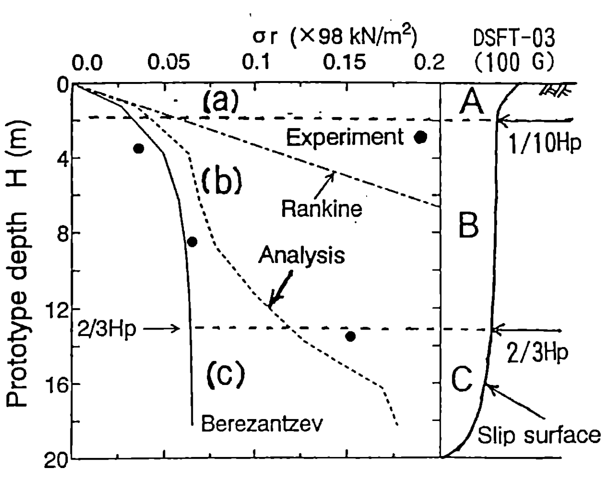


Figure 8 Earth pressure on shaft wall (Fujii et al.)

introducing a factor α which is an experimentally deduced factor considering the effect of wall stiffness of shaft.

Rigorous mathematical formulation of the influences of shaft stiffness and the geometry of the shaft on wall pressure is presented by the paper of Bulychev et al., dealing with diaphragm wall construction as a contact problem of the theory of elasticity. Examples are given in the paper, demonstrating its capability of taking into account the effects of shaft stiffness and the shaft cross-sectional geometry on wall pressure.

4 CONCLUDING REMARKS

There are still accidents occurring due to unexpected reasons, inadequate construction control, but we also face with soil conditions which has less experience before, such as residual soil, extremely soft clay, sometimes with soil improvement methods. Case records of this sort are most valuable for future design.

Recent availability of FEM computer codes enables design engineers to perform sophisticated analysis, taking detailed construction sequence into account. Extensive site investigation with laboratory testing comparable to the level of FEM sophistication is absolutely necessary to improve our ability of prediction.

Accumulated database should be complied in a systematic manner in our geotechnical community which would be beneficial for many designers to have a reference in his/her own project.

More research is needed in the area of three dimensional excavation behaviour such as rectangular shaft excavations.

The papers presented in the Proceeding will provide a useful and valuable reference to solve these problems.

REFERENCES

Berezantzev, V.G. 1958. *Earth pressure on the cylindrical retaining walls*, Brussels Conf. on Earth Pressure Problems, II: 21-27

Symposium Papers reviewed in this Report

Abe, Y and Muramatsu, M. *A study on the displacement of neighbouring ground caused by the excavation of shafts.*

Batten, M., Powrie, W., Boorman, R. and Yu, H. *Measurement of prop loads in a large braced excavation during construction of the JLE station at Canada Water, East London.*

Bolt, A.F., Dembicki, E. and Horodecki, G.A. *The failure mechanism of the trench wall caused by additional soil pressure.*

Breymann, H., Fuchsberger, M. and Schweiger, H.F. *Deep open excavation in soft plastic ground in Salzburg, Austria.*

Bulychev, S., Fotieva, N.N. and Sammal, A.S. *Design of underground structure closed in plan erected with application of the diaphragm wall technique.*

Carter, M.D., Bailey, R.P. and Dawson, M.P. *Jubilee Line Extension, Westminster Station design.*

Chang, J-D. and Wong, K.S. *Apparent pressure diagram for braced excavations in soft clay with diaphragm wall.*

Crawley, J.D. and Stones, C.S. *Westminster Station - deep foundations and top down construction in central London.*

Dawson, M.P., Douglas, A.R., Linney, L. and Friedman, M. *Jubilee Line Extension, Bermonsey Station box, design modifications, instrumentation and monitoring.*

de Boer, F. and van der Eem, H.M. *An undergound tunnel beneath Amsterdam central station.*

De Moor, E.K. and Stevenson, M.C. *Evaluation of the performance of a multi-propped diaphragm wall during construction.*

Enami, A., Morishita, H., Ogihara, M., Homma, M., Tezuka, H. and Hiramatsu, Y. *Earth pressure acting on a deep circular shaft wall.*

Fernie, R. and Suckling, T. *Simplified approach for estimating lateral wall movement of embedded walls in UK ground.*

Fernie, R., Kingston, P., St John, H.D., Higgins, K.G. and Potts, D.M. *Case history of a deep 'stepped box' excavation in soft ground at the sea front - Langney Point, Eastbourne.*

Fujii, T., Hagiwara, T. and Kusakabe, O. *Active failure mechanism of a deep circular shaft in dry sand.*

Gourvenec, S., Lacy, M., Powrie, W. and Stevenson, M. *Observation of diaphragm wall movements in Lias Clay during construction of the A4/A46 Bypass in Bath, Avon.*

Horiuchi, T. and Shimizu, M. *Settlement of soft ground and damage of wooden houses by braced excavation.*

Ishida, T., Sato, M., Tatsui, T. and Nakagawa, Y. *The cases of measurement of the pressure of the open cut with earth retaining wall.*

Maffei, C.E.M., Da Silva Guerra, E. and Leonardo Leite, R.L. *Case history of a ruptured multi tied-back retaining wall.*

Masuda, T. *A study on empirical correlation for lateral deflections of diaphragm walls in deep excavations.*

Nakagawa, S., Kamegaya, I., Kureha, K. and Yoshida, T. *Case history and behavioural analyses of braced large scale open excavation in very soft reclaimed land in coastal area.*

Nakai, T., Kawano, H. and Hashimoto, T. *Prediction of earth pressure and settlements due to excavation: influence of wall deflection process and wall friction.*

Nash, D.F.T., Lings, M.L. and Ng, C.W.W. *Observed heave and swelling beneath a deep excavation in Gault clay.*

Resin, V.I., Bibin, L.A., Ilyichev, V.A., Ukhov, S.B., Pankina, S.F., Kolybine, I.V., Lerner, V.G., Trusov, G.V. and Rudiak, M.S. *Manezhnaya Square Project - Geotechnical Aspects.*

Saji, S. and Numakami, K. *Reinforcement effect of composite earth retaining wall system on releasing strut.*

Tamano, T., Fukui, S., Mizutani, S. and Tsuboi, H. *Earth pressures acting on excavation side of braced wall in soft ground.*

Tanaka, H. *Undrained shear strength for passive earth pressure in excavation of soft clay ground.*

Tanaka, T., Toyokuni, E. and Ozaki, E. *Prismatic failure - a new method of calculatiing stability against boiling of sand within cofferdam.*

Toyosawa, Y., Horii, N., Tamate, S. and Suemasa, N. *Failure characteristics of sheet pile wall in centrifuge tests.*

Ueki, H., Moue, S., Kobayashi, S. and Sekiya, K. *In situ monitoring and analysis of a cut-and-cover tunnel on the bay-shore route.*

Ueno, K., Yokoyama, Y., Ohi, A. and Fujii, T. *Earth pressure acting on flexible circular shafts in sand.*