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New methods for better predicting soil behavior under earthquake loading

Nouvelles méthodes pour mieux prédire le comportement des sols sous des conditions sismiques

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ABSTRACT: Kiso-Jiban Consultants Co. Ltd. continues to be a pioneer in developing a fundamental understanding of the behavior of soils, especially under earthquake loading. Kiso-Jiban's research activities are concentrated on new methods of soil monitoring, sampling, testing and analysis for predicting the behavior of ground during and after earthquakes. In this paper, five new capabilities introduced by the company are highlighted: (1) Very high quality soil sampling in which the soils is frozen in situ to preserve soil structure, (2) The world's largest laminar shear box for laboratory recreation of liquefaction conditions, (3) Network of liquefaction sensors for real time monitoring of the occurrance and extent of liquefaction in order to facilitate lifeline decisions of gas supply, (4) 3-Dimensional seismic response analysis using the "complete method" which directly solves for the behavior of free-field/soil/foundation/structure as an integrated whole, and (5) New application for pile-integrity testing to identify earthquake induced cracks in large installations of concrete group piles with thick pile caps. Several of these innovative methods and technologies proved to be very valuable in the aftermath of the 1995 Hyogoken Nanbu (Kobe) Earthquake when there was great urgency to evaluate and prioritize the reconstruction work.

RESUME: Kiso-Jiban Consultants Co. Ltd. continue d'innover dans le développement de l'étude du comportement des sols, particulièrement sous des conditions sismiques. Kiso-Jiban concentre sa recherche sur les nouvelles méthodes de surveillance, d'échantillonnage, d'essai et d'analyse servant à prédire le comportement des sols durant et après des séismes. Cet article décrit cinq nouvelles expertises développées par la compagnie: (1) Prélèvement d'echantillons intact du sol, qui est congelé sur place pour conserver sa structure, (2) La plus grande boîte de cisaillement du monde, qui recrée en laboratoire les conditions de liquéfaction, (3) Réseau de détecteurs de liquéfaction pour surveiller l'apparition et l'étendu de la liquéfaction, à fin de faciliter les prises de décision futures, (4) Analyse tri-dimensionnelle de la réponse sismique en utilisant la 'méthode complète', qui résout directement les comportement des sol éloigné/sol/fondation/structure tout ensemble, (5) Nouvelle application pour évaluer l'intégrité des pieux de foundation, en identifiant les fissures induites par des séismes dans les grandes installations de pieux groupés à grands longrines. Plusieurs de ces méthodes et technologies innovatrices se sont averées très utiles après le séisme de Hyogoken Nanbu (Kobe) en 1995, à ce moment où il y avait un besoin urgent d'évaluer et de classer les travaux de reconstruction en ordre de priorite.

1 INTRODUCTION

Since its founding in 1953, Kiso-Jiban Consultants Co. Ltd. has committed itself to a pioneering role in developing a fundamental understanding of the behavior of soils under environmental and engineering loadings, with earthquake loading being a particular emphasis. To this end, in addition to providing comprehensive consultancy services, Kiso-Jiban is very much involved in a broad range of research activities, most of which are concentrated on new methods of soil monitoring, sampling, testing and analysis for predicting the behavior of ground during and after earthquakes.

In the body of this paper, five new technologies introduced by Kiso-Jiban are highlighted:

1. Very high quality soil sampling: Frozen samples capture substantially more of the true liquefaction resistance and dynamic properties of soils.
2. Large scale laminar shear box: The world's largest shear box recreates liquefaction and associated large ground displacements (ground flow) in the laboratory so that the effects on full scale piles, underground structures and lifeline systems can be evaluated.
3. Liquefaction sensors: Network of newly designed liquefaction sensors in Tokyo monitors the occurrence and extent of liquefaction in real time. Status information is continuously reported to gas lifeline decision centers so that in the case of earthquake-induced liquefaction, the supply of natural gas can be stopped to areas where pipelines may be damaged.
4. 3-Dimensional seismic response analysis: Breakthrough 3-D analysis using the "complete method" directly solves for the behavior of free-field/soil/foundation/structure as an integrated whole, therefore eliminating losses in accuracy introduced by sub-structuring steps and assumptions.
5. Pile integrity tests: New application of pile integrity testing to identify earthquake-induced cracks in large installations of concrete group piles with thick pile caps.

2 MOTIVATION

Kiso-Jiban has a very keen interest in earthquake damage mitigation because of the high level of earthquake threat in Japan. Beginning in 1978, as part of its commitment to being a leader in earthquake-related geotechnical engineering, Kiso-Jiban has sent out teams of specially trained engineers to perform post-earthquake damage investigations. The teams have compiled detailed records of field investigations of damage caused by major earthquakes in Japan (e.g., Kiso-Jiban, 1978, 1983, 1993; Kobe City Development Authority, 1995) and overseas (e.g., Kiso-jiban, 1989, 1990, 1994). The most important thing the teams do is to identify new damage patterns, if any, and develop methods to prevent such damage in future earthquakes.

The importance of this key role was graphically illustrated during the 1995 Hyogoken Nanbu (Kobe) Earthquake. The Kobe earthquake occurred on a fault directly beneath the city of Kobe, and caused the highest earthquake-related loss of life in Japan this century, except for that from the 1923 Great Kanto earthquake.

Ground motions in Kobe were much stronger than those measured during larger earthquakes in Japan. The location of the fault and the direction of rupture propagation during the Kobe earthquake were particularly unfortunate. The near source was densely populated, having highly developed infrastructure. The direction of rupture was aimed directly at this area.

During the Kobe earthquake, many catastrophic failures occurred. Not only did extensive liquefaction in the reclaimed areas result in the devastation of Kobe's port facilities, but all sorts of engineered structures, such as buildings, bridges, roadways, etc. suffered extensive damage. Several multi-story buildings actually toppled into the street. There was real shock at the extent of damage to relatively new engineered structures, because many people had come to believe that modern design codes were sufficient to protect the public from this kind of wholesale destruction.

Immediately following the Kobe earthquake, Kiso-Jiban Consultants, together with many other Japanese and international consulting companies and contractors, committed themselves to the task of identifying hazards, recommending repair works and developing new design and analysis procedures in order to help communities avoid loss of life, damage and disruption due to future earthquakes. Several of the innovative methods and technologies discussed in the final five sections of this paper proved to be very valuable in the aftermath of the Kobe earthquake when there was great urgency to evaluate and prioritize the reconstruction work.

The large number of failures of engineered structures and installations, together with the enormous amount of high quality data about the earthquake, has both prompted and enabled government agencies, research institutions, practicing geotechnical engineers and consulting firms to review their current methodologies for seismic design and analysis.

For example, bridge failures, extensive liquefaction and associated ground flows during the Kobe earthquake triggered the revision of the seismic design code for highway bridges in Japan, which is compiled by the Japan Road Association. In the previous guideline, geographic areas were assigned design shaking levels primarily based on their attenuation characteristics. Smaller but closer faults were not deemed as dangerous as the very large offshore faults.

Therefore, in the past, an assessment of the likelihood of soil liquefaction was made assuming an offshore-type ground motion. No provision was made to actually evaluate the likelihood of ground flows such as were prevalent in Kobe, although engineers were advised to use caution about the potential for ground flow.

In the revised guideline, an additional level of design ground motion is introduced which is representative of the Kobe experience, i.e., motions generated by potential earthquakes located on faults near to the site. These faults are located in the crust and are typically much shallower than faults located in the offshore subduction zone. Furthermore, the revised design procedure for highway bridge foundations now requires explicit and quantitative consideration of ground flows induced by soil liquefaction.

Many of the improvements in the design codes were made possible by recent advances in geotechnical engineering. Improved methods for sampling, testing and analyzing soils have directly contributed to making the codes more intelligent and effective. The remaining sections describe five such advances, and highlight the contribution these new technologies have already made to earthquake hazard mitigation.

3 HIGH QUALITY SOIL SAMPLING

For the purpose of obtaining high quality undisturbed soil samples, Kiso-Jiban has developed a sampling technique by first freezing the ground in-situ using liquid nitrogen injected through a pipe inserted into the ground. When the soil mass at the desired depth is frozen, undisturbed core samples are obtained by either coring, or by excavating the entire frozen block and drilling core samples out from the block.

The frozen sampling technique has been used successfully to obtain high quality undisturbed soil samples for purposes of evaluating dynamic properties. This procedure is particularly useful in obtaining intact samples of gravelly soils where, because of the existence of large grain particles, conventional soil sampling techniques cannot be used. Figure 1 shows an example of a gravelly soil sample obtained by the in-situ freezing method.

In Japan, Pleistocene gravel layers are widespread and are often encountered in civil engineering construction works. There have been circumstances in the past where loose gravelly soils have liquefied, much like the situation with loose sands. The

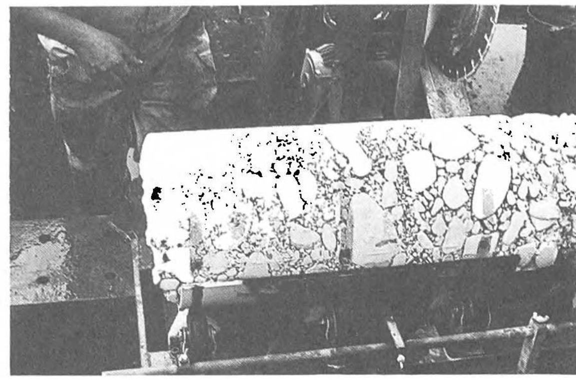

Figure 1: Freeze sampling using a large diameter sampler to obtain undisturbed samples of gravelly soils

prevalence of these loose gravelly soils, taken with the uncertainty of their stability during earthquakes, underscores the importance of understanding their in-situ properties. In the past, few studies were undertaken due to the difficulty of obtaining an undisturbed sample of the gravelly materials.

Now, high quality samples can be obtained using the in-situ freezing sampling technique. The results from cyclic triaxial tests reveal that samples obtained by in-situ freezing sampling method have higher shear modulus, higher damping ratio, greater degradation of modulus at small strain level, and higher undrained cyclic strength when compared to results from conventionally sampled specimens or to reconstituted specimens. These differences in strength are due to the effects of sample disturbance (Kokusho and Tanaka, 1994).

Kiso-Jiban has also employed the in-situ freezing sampling technique to investigate the dynamic properties, cyclic strength, and liquefaction potential of decomposed granite (locally referred to as Masa soil) which experienced extensive liquefaction during the Kobe Earthquake. Previous to the earthquake, decomposed granite was thought to be resistant to liquefaction because of the fairly large proportion of gravel it contained and its well-graded nature.

Immediately after the Kobe earthquake the in-situ freezing technique was used to obtain samples of reclaimed soil in the dock area of Port Island, where extensive liquefaction occurred. One reason this method was used was because the reclaimed material contained gravel. Another reason was that by using this sampling method, the port authority could obtain an assessment of the liquefaction resistance of the material which represented as closely as possible the real strength of the in-situ material, with minimal reductions in strength caused by disturbances during sampling procedures.

4 LARGE SCALE LAMINAR SHEAR BOX

Kiso-Jiban has built the world's largest laminar shear box to simulate actual ground conditions during liquefaction, and to investigate the effects of liquefaction on full scale piles, other underground structures, and lifeline systems (Ishihara et al., 1996). The box is truly huge, having inside dimensions of 11.6m in length, 3.1m in width, and 6.0m in height. The reason for the huge size of shear box is to overcome problems caused by the low confining pressures in smaller scale 1-g models, and to simulate real ground conditions on full scale piles and other structures modeled as closely to actual size as possible.

Aside from its hugeness, the significant features of this shear box are the maximum deformation that can be obtained compared with existing shear boxes (the allowable shear strain is 50% while the over-all maximum shear displacement is limited to 1.5m), the fact that the soil can be used over and over through the process of boiling, and the efficient soil removal method employed after testing.

This shear box and its appurtenances, shown in Figure 2, are located on a 12m x 12m shaking table at the earthquake engineering laboratory of the National Research Institute for

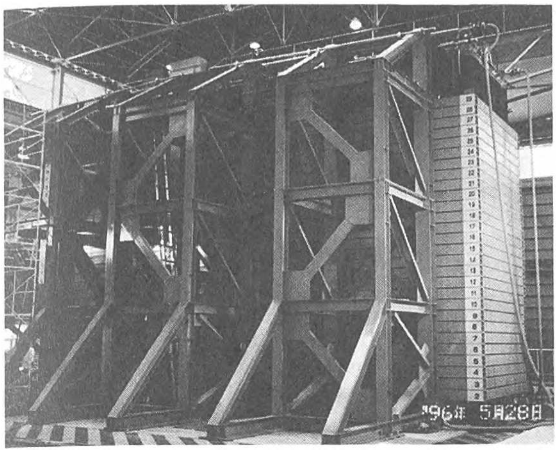

Figure 2: A view of the large-scale laminar shear box

Earth Science and Disaster Prevention. The experimental system also includes a sedimentation pond, temporary soil storage, a regulating yard, soil storage, and an elevated water tank. A hose pipe connects the shear box with the sedimentation pond which in turn is connected to the temporary soil storage via a soil conveyor. A water supply and drainage system has been incorporated into the shear box, the sedimentation pond and the water tank.

Tests can be performed repeatedly without exchanging the soil because the soil can be "boiled up" and repositioned in a pre-liquefaction configuration. After each test, water is introduced from the bottom, top and sides of the box at a rate of 2 tons/min. This is sufficient to induce boiling of the soil.

At the end of a test series, the soil can be evacuated rapidly by injecting water into the box to form a slurry. Water is also rapidly injected in the downstream of the evacuation valve, thereby producing a strong suction. With this procedure, soil can be removed from the box at a rate of 1 ton/min.

The laminar shear box consists of a series of 29 frames made of H200x200 steel separated by a gap of 1cm. Low-friction rollers are placed between these frames in order to minimize friction between the frames. The displacement between frames is limited to 10.5cm through the use of stoppers (slots and shear bolts) installed at the four corners of the frames. A lateral support system is provided in order to ensure the integrity of the frames and to maintain the smooth horizontal movement of the shear box during liquefaction. Furthermore, the box is designed to prevent swaying and rocking of frames and self-oscillation of the structural components (the natural frequencies of the components are set higher than 20 Hz). The load capacity of the system is 500 tons while the weight ratio of the frame to the soil is in the range of 9-12%, which is similar to those of existing small-scale shear boxes.

5 LIQUEFACTION SENSOR

Kiso-Jiban has developed a liquefaction sensor that detects, within a very short time period following an earthquake, the occurrence and extent of soil liquefaction. The advantage of this sensor is that no sophisticated instrument is employed underground, making this sensor more reliable than conventional pore water pressure transducers. Moreover, because most of the detecting devices can be accessed from the ground surface, maintenance work is simplified.

The adaptability of the liquefaction sensor has been extensively validated through various laboratory shaking table tests and boiling tests, as well as in-situ vibration and flow tests.

At present, liquefaction sensors have been installed at 20 sites across the Tokyo Metropolitan area. The data recorded by the sensors are recorded by computers and transmitted quickly to a central office through a wireless network. If certain areas have been assessed to have liquefied based on the data and damage to gas pipelines is predicted, the supply of gas is immediately closed to prevent the expansion of damage to other facilities.

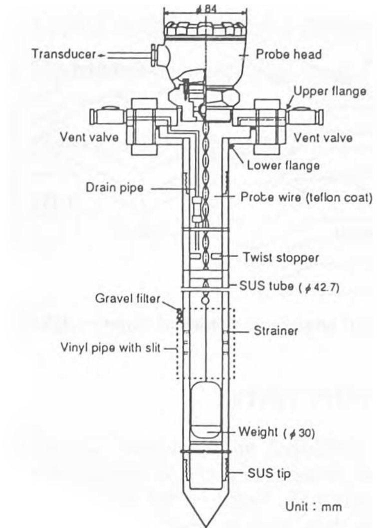

Figure 3: Schematic diagram of liquefaction sensor

The sensor works by measuring the water level in a pipe inserted into the ground. The sensor consists of a hollow pipe (inside diameter 32.9mm) which is buried underground. Groundwater enters the pipe through a strainer. A water level detection sensor continuously measures the water level within the pipe. The detection sensor used is a modification of the capacitance type level gauge that is widely used for water tank level gauges. The strainer section, which is 100 mm long and has openings of 2mm in diameter, is positioned in the sandy layer which is susceptible to liquefaction. A filter is provided in the vicinity of the strainer to prevent the entry of soil particles into the pipe (Koganemaru et al., 1996). A schematic diagram of the sensor is shown in Figure 3.

6 THREE DIMENSIONAL SEISMIC RESPONSE ANALYSIS

Kiso-Jiban has achieved a breakthrough in solving 3-dimensional dynamic soil-structure interaction (SSI) problems. A new, remarkably efficient procedure has been developed based on the "complete method" which solves the entire 3-D dynamic SSI system together with all the boundary conditions in a single step. In this procedure, the equation of motion is reformulated in terms of the interaction displacements instead of the absolute or relative displacements. It is currently being validated using the test results obtained from experiments using the large scale shear box discussed earlier. This 3-D procedure can be applicable and very powerful to many problems such as nuclear plants, dams, shield tunnels, soil-pile interaction systems, etc.

In this new procedure, the surrounding free field is not limited to a horizontally layered system; problems with complex geometry can be easily included in the model. The significant non-linear effects due to large shear deformation in soils can be taken into account by the introduction of equivalent linear method.

The new procedure is implemented through the program SuperFLUSH/3DC based on the complex response method (Namita et al., 1995). The analytical model consists of 2 parts: free field zone and 3-D finite element zone. The wave generated at the 3-D zone can be propagated into the free field zone. The viscous dashpot boundaries or energy transmitting boundaries can be furnished at the model boundaries to avoid reflection of the waves. A typical analytical model is shown in Figure 4. Solving for example a 3-D problem with 22,000 degrees of freedom takes approximately 20 hours per frequency on an Engineering Work Station (EWS).

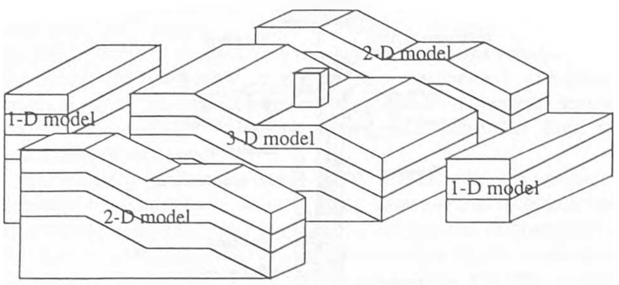

Figure 4: A typical analytical model of SuperFLUSH/3DC

7 PILE INTEGRITY TESTS

Kiso-Jiban has developed an innovative method of obtaining quick, qualitative assessments of the likelihood of earthquake damage to concrete piles based on the pile integrity test (PIT). The method was developed in response to the urgent need to evaluate the structural integrity of cast-in-place pile foundations in Kobe, just after the 1995 earthquake. Post-earthquake investigations by excavating the ground adjacent to piles and by lowering borehole video camera inside the hollow piles revealed the presence of cracks in almost all the piles inspected, even though the pile caps usually did not appear to have any damage. With the enormous quantity of pile foundations for elevated highways in the area and with the possibility that they were also cracked as a result of the earthquake, a fast and economical method of checking these pile foundations was required.

The original PIT method involves striking the center of the pile top with a hammer and recording the reflected sound waves as they arrive back at the pile top. The key discriminator for damage is waves returning before the wave reflected off the pile bottom should arrive: this indicates a reflective surface - a crack in the pile - somewhere above the pile bottom.

In Kobe, most, if not all of the highway pier foundations consist of a large number of closely spaced (twice the pile diameter or less) concrete piles tied to a pile cap having a thickness on the order of the pile spacing or greater. The structural complexity of this group pile/pile cap system causes two difficulties: (1) the top of the pile is not accessible. The hammer must be applied to the top of the pile cap just above the pile center; (2) The resulting sound waves are not confined to travel paths strictly within the pile being tested. There are some returning signals from adjacent piles, and from the pile cap. The net result being that the recovered signal is significantly more complex than in the single pile case, but can be interpreted qualitatively to estimate the extent of pile damage.

A total of 159 pile foundations supporting the Wangan Route of the Hanshin expressway in Kobe were investigated by Kiso-Jiban and other consultants using both PIT and borehole video camera (Hanshin Expressway Public Corp., 1996). The results obtained from PIT were compared to the enhanced images obtained from the Borehole Image Processor (BIP). The observed data shows a significant correlation between the number of peaks in the velocity reflector and the number of cracks found using BIP. This observation indicates the possible use of such correlations in estimating the number of major cracks in piles of foundations affected by large earthquakes (Enomoto et al., 1996).

The effectiveness of PIT has also been validated through model tests and numerical analyses. A typical comparison of the data obtained by PIT and BIP is shown in Figure 5.

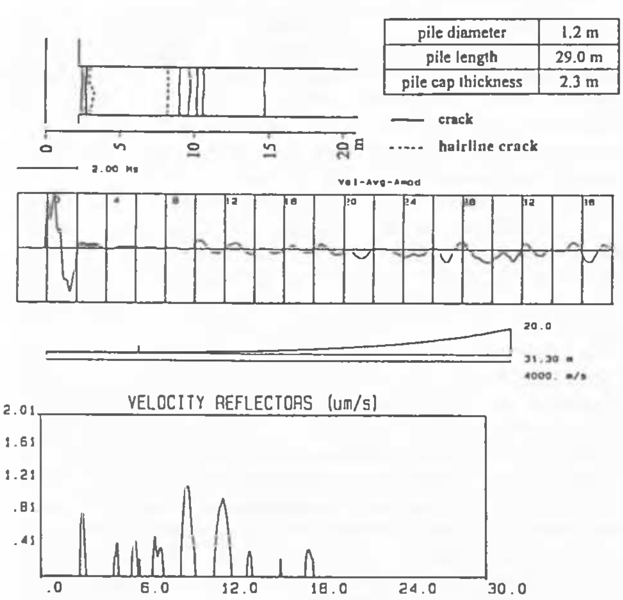

Figure 5: Comparison between PIT and BIP Data

8 CONCLUDING REMARKS

Being a geotechnical engineering firm, Kiso-Jiban is not only concerned with providing comprehensive consultancy services, but is also very much involved in a wide range of research activities geared towards the growth of knowledge and technical know-hows pertaining to the earthquake geotechnical engineering profession. Through these various research activities, some of which are briefly introduced in this paper, Kiso-jiban is showing its commitment to the enhancement of the current understanding of ground response during earthquakes in particular and to the development of an earthquake-resistant environment in general.

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