Journal of Japan Association for Earthquake Engineering, Vol.4, No.3 (Special Issue), 2004

RESTRATION OF PORT FACILITIES AFTER THE 1995 HYOGOKEN-NAMBU EARTHQUAKE

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ABSTRACT: It is well known that the port facilities in Kobe Port suffered severe damages during the 1995 Hyogoken-Nambu earthquake. Especially, many caisson type quay walls were damaged during the earthquake. In order to mitigate hazards and losses due to earthquakes, seismic design methodologies have been developed and revised after each past earthquake event. The design practice of port structures in Japan introduced a performance based design concept as a result of damage investigations after the 1995 Hyogoken-Nambu earthquake. The restoration of Kobe Port was based on following philosophies: 1) quick recovery of the functions of the port, 2) improve seismic performance, 3) renewal with change the function of facilities and 4) continued operation of the port during restore works.

Key Words: Liquefaction, Port facilities, Performance-based design, Shake table test, Restoration work

INTRODUCTION

At the time of the 1995 Hyogoken-Nambu earthquake, the Kobe Port had 186 quay walls, around 90 percent of which were caisson type walls. Most of these quay walls moved toward the sea about 5m maximum and inclined about 4 degrees toward the sea. About the same order of magnitude of settlement was induced in the soil backfill behind the walls due to the strong earthquake motion.

Geotechnical investigations including in-situ soil freezing sampling, shake table tests and numerical simulations were conducted in order to understand the mechanism of caisson wall damage. The displacement of the caisson obtained from the shake table tests agreed with those measured after the earthquake. The results of these investigations (Inagaki et al. 1996) suggested that the increase in excess pore water pressure, in the foundation soil underneath the caisson and the backfill soil, significantly increased the deformation of the caisson walls. Also, the results of the effective stress analyses were consistent with those measured, including the failure mode and deformation, suggesting that the cyclic behavior of soil can explain the actual damages.

From the lessons learned from the earthquake disaster, performance-based design methodology was introduced instead of a conventional seismic design. Two levels of earthquake motions are typically used as design reference motions, defined as follows; Level 1: the level of earthquake motions that are likely to occur during the life-span of the structure, Level 2: the level of earthquake motions associated with infrequent rare events, that typically involved very strong ground shaking.

Conventional seismic design is based on providing capacity to resist a design seismic force, but it does not provide information on the performance of a structure when the limit of the force-balance is exceeded, especially, in case of the level 2 design input motion proposed by the Japan Society of Civil Engineers (2000).

The restoration of Kobe Port was based on following issues:

1) Quick recovery of functions of the Kobe Port
   To secure the shipping serviceability for emergency supply or restoration supply, availability of damaged facilities for temporary/emergency use depends on the residual capacity of the structure system, necessity and availability of transportation from the port area to the onshore/inland areas. To minimize the economic damage due to the defects of port function, quick recovery was needed.
2) Improve seismic performance of port facilities
   The seismic performance of damaged facilities should be improved according to their degree of importance. In the case of restoration of quay wall, the recovered structure may be complex, i.e. combined with damaged structure and add-on structure. The conventional seismic design method cannot be applicable to such complex structures.
3) Renewal with change of function
   In order to change in the social/economical requests of port facilities, renewal of outdated facilities with change or improvement of function was needed.
4) Continued operation of the port during the restoration works
   To mitigate social and economic impacts, continue the port operation during urgent restoration works. Following the earthquake, both emergency activities and recovery related activities had to be maintained.

RESTORATION METHODS

Typical restoration methods

The method for restoration was selected based on an availability/restriction of construction area, construction period, cost, construction materials and the extent of damage to the facility of interest. Earthquake resistance should be improved according to the importance of facilities. The seismic performance of port facilities should be evaluated by numerical or experimental simulations.

The basic restoration techniques are summarized as followings: 1) Reduce the earth pressure acting on the structure, 2) Put additional structure to the damaged structure, and 3) Remediate/replace the liquefiable soil. Depending on the intensity of acceleration and soil conditions, liquefaction of near-structure region soil and associated ground failures may occur, and could significantly affect the port facilities. Improvement techniques for the earthquake resistance vary depending on the specific conditions of structures. Combination of more than one technique shows more effective resistance.

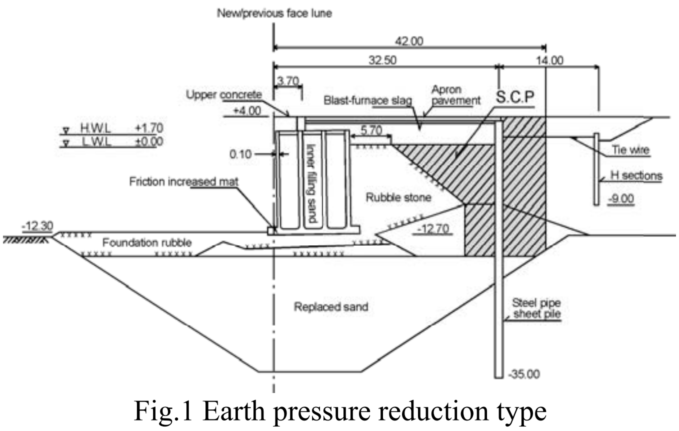

Fig.1 Earth pressure reduction type

Various restoration methods were adopted in Kobe Port based on the structural and the geotechnical conditions, the degree of importance and function of the facilities as shown in Fig.1-Fig.3. Pre-cast structures such as jacket, were effective to shorten the recovery time, as shown in Fig.3. The jacket bodes can be assembled at a factory in undamaged region.

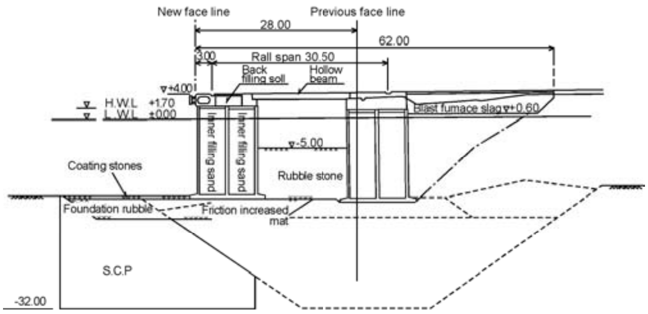

Fig.2 Detached structure type (caisson)

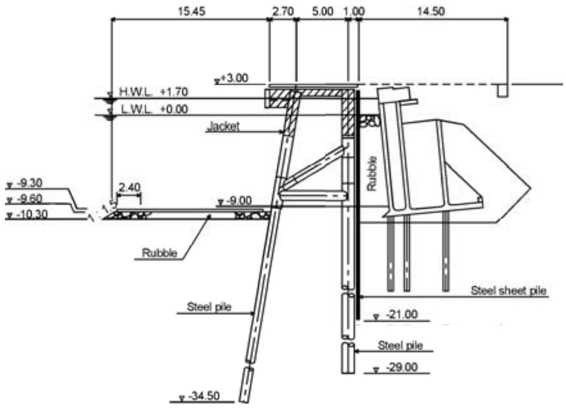

Fig.3 Pre-cast jacket type

Case study of the detached structure

A new structure was constructed in front of the damaged caisson wall with spacing between them as shown in Fig.2. This method can be adopted when there is no restriction of water spaces in front of the new structure. If the damaged caisson itself is unstable, the backfill soil is replaced with lightweight materials such as blast furnace slug or improved the backfill soil in order to reduce the earth-pressure acting on the damaged structure.

In order to increase the reaction force against damaged structure's sliding force during the earthquake, rubble stone is put between additional structure and damaged structure.

The damaged quay wall was designed with seismic coefficient, k=0.15. The caisson moved 1.9m toward the sea during the 1995 Hyogoken-Nambu Earthquake. To improve the seismic coefficient, k from 0.15 to 0.25, a new add-on detached caisson was installed. As shown in Fig.2, the stability system of the restored structure section is complicated.

In order to evaluate the seismic performance of the restored structure, underwater shake table test was conducted with the model scale of 1/22. Three-dimensional shaking was applied using the subsurface motion recorded at a depth of 32m by the vertical seismic array at Port Island. The similitude in 1G gravitational field for soil-structure-fluid system (Iai, 1989) was adopted for the test. In order to obtain a comprehensive behavior of the dynamic performance of the restored quay wall during the earthquake shaking, time histories of the response of the quay wall obtained using the underwater shake table are shown in Fig.4. The excess pore water pressure in the remediated backfill region (W6) and foundation region (W12) of the front caisson did not increase. However, the excess

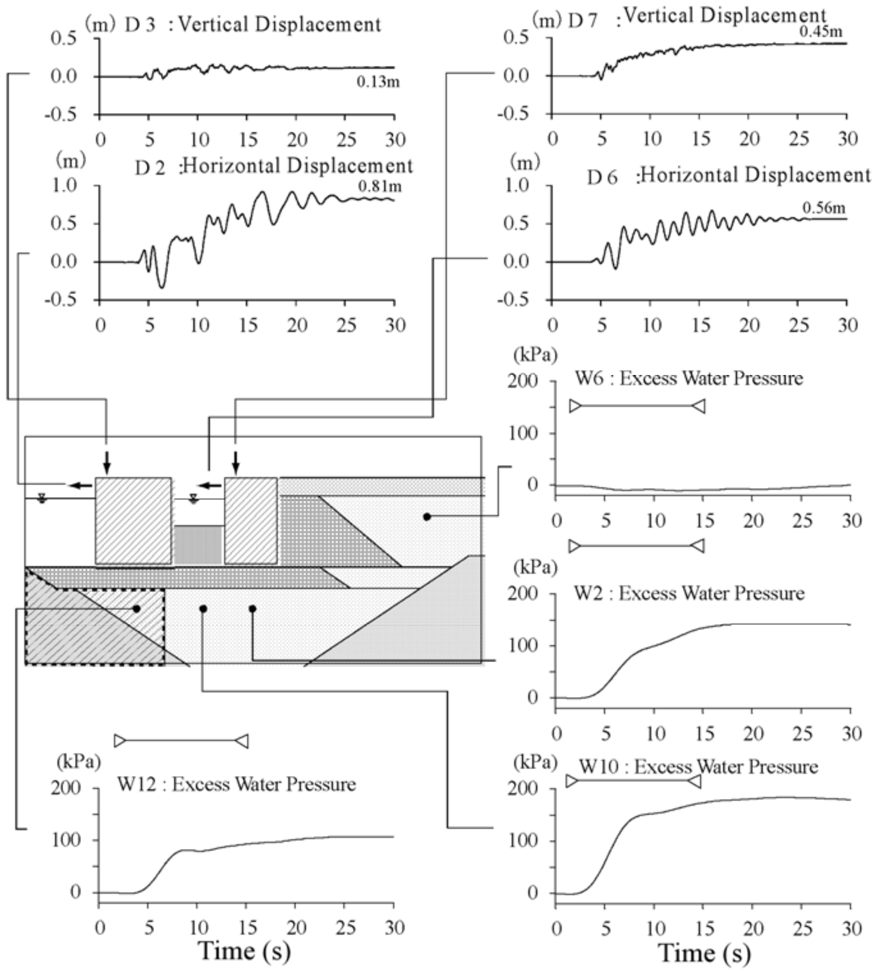

Fig4 Underwater shake table test results (prototype scale)

pore water pressure (W10) at untreated foundation region under the rubble stone between both caissons reached the overburden pressure. The excess pore water pressure ratios in the W10 region increased by about 90% during the earthquake, but this increase did not affect the quay wall deformation. The horizontal displacement time histories of both caisson (D2 and D6) show good performance during the earthquake shaking.

CONSIDERATION OF NUMERICAL / EXPERIMENTAL SIMULATIONS

Numerical and experimental simulations are powerful tools for assessing the performance of the restored facility. However, from practical point of view, the accuracy of these simulations need to be verified. As shown in Fig.6, we have several methods to evaluate the seismic performance of port facilities such as: 1) Actual damage investigation, 2) Model tests, 3) Numerical simulations and 4) Full/Large-scale experiments. As shown in Fig.5, these methods are connected by ‘complement’ or/and ‘verification’ lines in order to improve the accuracy of simulations.

1) Actual damage investigation

The data sets we can obtain are as followings: a) Before an earthquake: design documents, sounding data, boring log, etc., b) During an earthquake: strong motion records, and c) After an earthquake: damage investigation data, etc. The lack of data during an earthquake is serious problem.

2) Model tests

In order to study the soil-structures interactions, serious problem is ‘similitude’ relationships between a model and a prototype, even in the case of centrifuge tests. Then, how can we evaluate the accuracy of the model test results? Model tests have an advantage in obtaining 'dynamic behavior data' during an earthquake. The disadvantages are they are rather expensive and take relatively long time to conduct.

3) Numerical simulations

Generally, a constitutive law is based on laboratory soil test data, such as a triaxial compression test. Problems exist in finite element modeling using 1D, 2D or 3D and arrangements of input parameters. Then, how can we evaluate the accuracy of the numerical simulations? However, we can obtain useful information such as element stress condition including time history of the excess pore water pressure of the ground. The disadvantages are that it is rather expensive and it needs skilled operator.

4) Full/Large-scale experiments

In order to improve the model test techniques, similitude law, the numerical analysis technique and the accuracy, full/Large-scale instrumented experiments are needed. A Full/Large-scale experiment is often difficult to conduct, because it is extraordinarily expensive and takes long time. The National Research Institute for Earth Science and Disaster Prevention (NIED) Japan has been constructing the 3-D Full Scale Earthquake Testing Facilities (http://www.bosai.go.jp). The UCSD, USA has been constructing the Large High Performance Outdoor Shake Table (http://www.nees.org/EQ/sites/p2_ucsd.html).

In order to assess the seismic performance of structures during liquefaction, the US-JAPAN joint research project (Sugano et al., 2002) was implemented under the cooperation of 14 organizations.

5) Actual quay wall observatory

Hokkaido regional Development Bureau, Ministry of Land, Infrastructure and Transport Japan constructed 5.5m design depth caisson type quay walls with about 180 channels of instruments such as seismographs, pore water pressure gauges, accelerometers, velocity sensors and large earth pressure gauges (1m by 1m), etc. in Kushiro Port (Sasajima et al., 2004). The five year observation project started on April 1, 2002.

CONCLUSION

Based on the results from the study of the 1995 Hyogoken-Nambu Earthquake, a seismic performance based methodology is introduced. In order to assess/evaluate the seismic performance, new simulation techniques need to be introduced in the technical standards for port facilities in Japan. However, in practice, it is not easy to incorporate simulation techniques such as dynamic analyses and model tests. To brush up the seismic performance based methodology, it is still necessary to collect actual damage investigation data as well as model test data and numerical simulation data, and feed them back to practice with interpretation.

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(Submitted: March 31, 2004)

(Accepted: June 22, 2004)

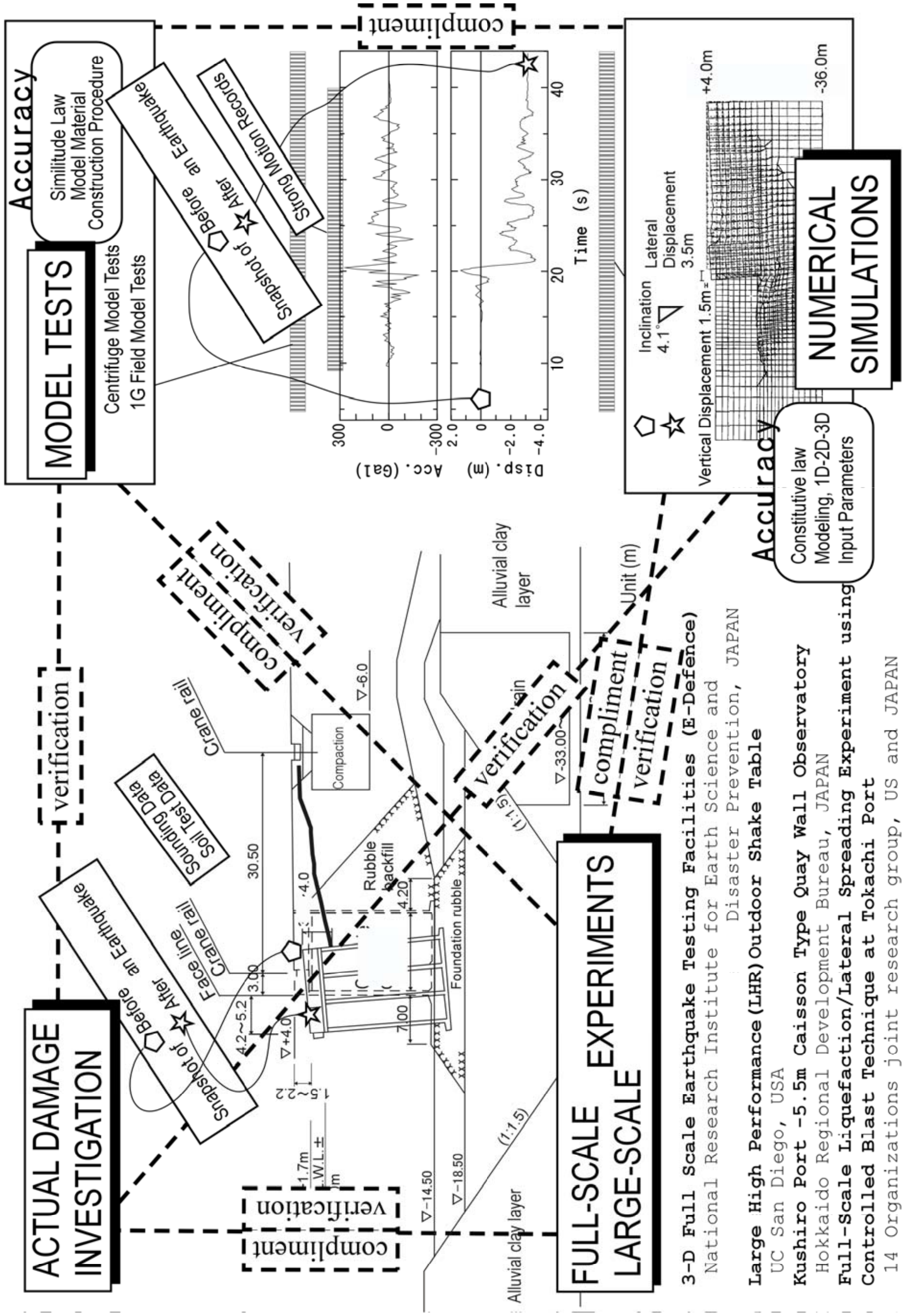

Fig.5 Mutual complementally relationship