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Special Contribution

Measures for Earthquake– and Tsunami–Resilience Enhancement of Industrial Parks in Bay Areas

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During past earthquakes and tsunamis, industrial parks have been repeatedly damaged by the strong earthquake motions amplified by the soft reclaimed grounds, the liquefaction of the sandy soil, and its induced ground displacements, and tsunamis. Heavy damages to industrial parks caused by future earthquakes and tsunamis will make huge impacts on the safety and the security of the nations and the people, as well as the worldwide economic activities. Therefore, the enhancement of earthquake- and tsunami-resilience is one of most urgent national subjects in earthquake- and tsunami-prone countries such as Japan.

Keyword: earthquake, tsunami, industrial park, soil liquefaction, ground displacement, oil tank, earthquake-resilience enhancement

1 Damage to Industrial Parks during Past Earthquakes

1.1 Damage to oil tanks caused soil liquefaction and its induced ground displacement

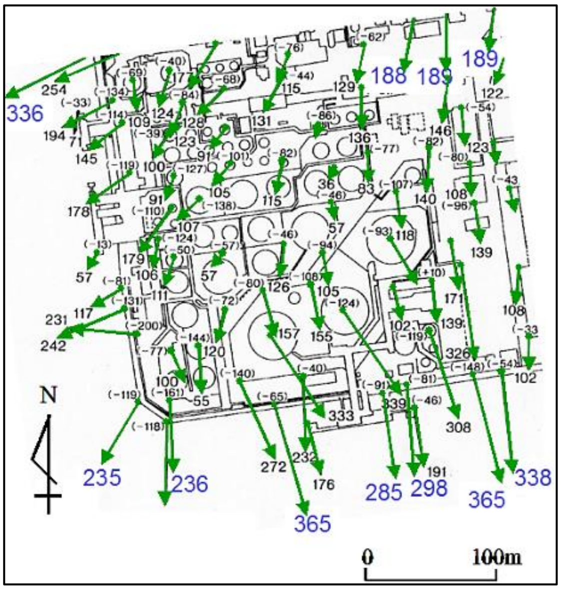
The soil liquefaction tilted and subsided a number of tanks for the storage of oil, high pressure gas and petrochemical products during past earthquakes in Japan. Figure 1 shows one of examples of tilted and subsided tanks due to a large decrease of the bearing capacity of the foundation ground by soil liquefaction during the 1995 Kobe earthquake [1]. Soil liquefaction has also ruptured oil protection walls as shown in Fugure2, which were caused by the 2011 Tohoku earthquake at Kashima petroleum plant along the Pacific coast.

Figure 1 Tilting and Subsidence of Oil Tanks by Soil Liquefaction (1995 Kobe earthquake)

Figure 2 Damage to Oil Protection Wall (2011 Tohoku earthquake)

Oil protection walls have an import role to prevent the outflow of the oil from the tanks to the plant site as well as into the sea. The damage shown in Figure 2 recognized as again that a great length of oil protection walls remains un-reinforced against the soil liquefaction.

(a) Tank site in Kobe, Aerial photo taken two days after the earthquake



(b) Ground displacements（cm）

Figure 3 Ground Displacements of A Manmade Island in Kobe Caused by Soil Liquefaction (1995 Kobe earthquake)

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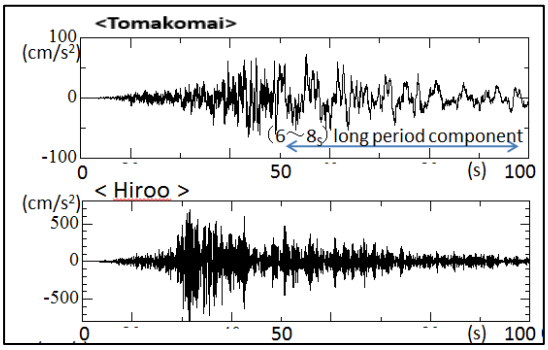
The soil liquefaction has caused one more serious damage to the oil and high pressure gas tanks during the past earthquakes. Figure 3(a) was an air photo taken two days after the 1995 Kobe earthquake over a manmade island reclaimed from the Osaka bay, where had been used for a tank site for storage of petrochemical materials and high pressure gas. The yellow color of the ground surface of the photo shows the sand boiled out of the ground due to soil liquefaction. This photo suggests that the whole area of the tank site liquefied. Figure 3 (b) shows the displacements of the quay walls and the ground surface. The vectors of the figure show the ground displacements in the horizontal direction and the numbers at the top of the vectors are the magnitude of the displacements in centimeters. The quay wall moved towards the sea 3 to 4m, and a whole area of the tank area of about 400m width and length, also moved 2 to 3m toward the sea [2]. These large ground displacements ruptured the pipeline of liquefied propane gas and a large amount of gas leaked. The residents in the neighborhood of the plant were forced to evacuate for about 24hours, but fortunately no explosion occurred.

1.2 Fires of tanks caused by long period earthquake ground motion

Long period components of earthquake ground motion caused sloshing vibration of the oil in floating roof type tanks, which resulted in big fires. During the 2003 off-Tokachi earthquake in Hokkaido, two tanks with a diameter about 40m fired and burnt down at an oil refinery plant in Tomakomai, as shown in Figure 4(a). Figure 4(b) shows the earthquake motions on the ground surface at two locations, Tomakomai and Hiroo. Figure 4(b) and (c) show that the earthquake ground motion observed at Tomakomai contained long period components of 6-8s, but, these long period earthquake motions were not observed in the record at Hiroo, where short period vibration components were dominant. The difference of dominant periods resulted from the difference of the ground conditions of the two locations. Tomakomai is located on soft surface soil with thickness about 2km. On the contrary, Hiroo is located on very thin surface soil of several meters thickness over hard rocks. The thick surface soil ground at Tomakomai amplified the long period components of the earthquake ground motion.

(a) Fires of oil tanks



(b) Observed accelerations

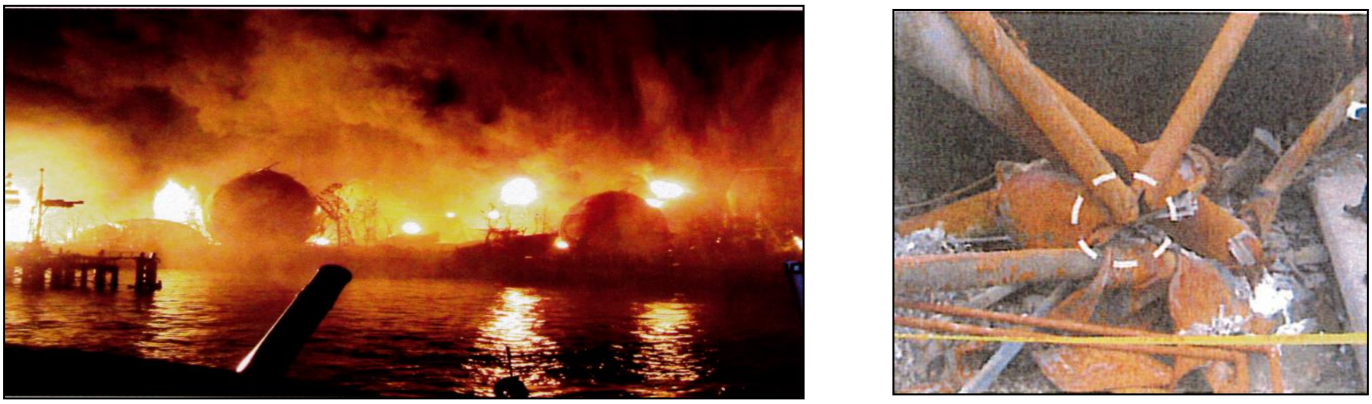
(c) Epicenter of the earthquake and observation points of earthquake

Figure 4 Fires of Oil Tanks Caused by Long Period Components of Earthquake Ground Motion (2003 off-Tokachi earthquake)

The diameters of the two fired tanks are about 40m and the natural periods of the sloshing vibration of the oil, depending on the depth of the oil, are estimated to be about 5 to 7s, close to the dominant periods of earthquake ground motion observed at Tomakomai. This long period earthquake ground motion induced sloshing vibration of the oil of the tanks, and the oil spilled out of tank was ignited by the metallic collision between the steel floating roof and the steel side wall. Fires of oil tanks by the sloshing vibration have been also reported during many past earthquakes such as 1964 Niigata earthquake and 1999 Kocaeli earthquake in Turkey.

1.3 Explosions of tanks caused by the short period earthquake ground motion

Besides the long period component of earthquake ground motion, the short period ground motions of less than one second have also caused the fires of oil and gas tanks due to the dynamic inertia forces of tanks and their contents. Seventeen spherical tanks of liquid propane gas in the Tokyo bay were collapsed and exploded during the 2011 Tohoku earthquake, as shown in Figure 5(a). The fire continued about one week, because the firefighters could not approach to the burning tanks. The firefighting was conducted from the sea by fireboats. A steel fragment of exploded tanks with a length of 1.5m and a width of 80cm scattered and dropped in the residential area 6km away from the plant.



(a) Seventeen spherical tanks were fired and exploded [3] (from Tokyo Fire Department)

(b) Breakage of steel braces

Figure 5 Fires of Spherical Tanks by Short Period Earthquake Ground Motion (2011 Tohoku earthquake in the Tokyo bay)

The direct cause of the collapse of the tanks is the breakage of steel braces of the support legs due to the dynamic inertia forces of the oil and the tanks. When the earthquake occurred, the tanks were filled with water instead of liquid propane gas for the periodic inspection. The water has about twice the weight of the liquid propane gas.

1.4 Fires of oil tanks due to tsunami

During the 2011 Tohoku earthquake, the tsunami caused serious damage to industrial parks. In Sendai port a big fire was induced at an oil refinery plant, as shown in Figure 6 (a). The cause of the ignition of the fire has not been clearly identified, because all of the workers of the plant were absent due to the tsunami evacuation. It is supposed that tank lorries were floated by the tsunami and hit the pipelines. Figures 6 (b) and (c) show the drift of a fuel tank for fishery boats, and the consequent fire on the sea surface at Onagawa. Tanks were lifted up by the buoyancy of the tsunami, and floated out by the continuous attacks of the tsunami.

(a) Fire of an oil refinery plant

(b) Flowing-out of fuel tanks for fishery boats

(c) Sea surface fire

Figure 6 Damage to An Oil Refinery Plant and Fires on Sea Surface Caused by The Tsunami (2011 Tohoku earthquake)

2 Damage Assessment of Industrial Parks in The Tokyo Bay

1.1 Soil liquefaction and ground displacement

Figure 7 shows the history of land reclamation in the Tokyo bay. These manmade islands include large areas of ground reclaimed prior to the 1964 Niigata earthquake. The phenomena of soil liquefaction and its caused damage were recognized from an engineering viewpoint for the first time at the time of the 1964 Niigata earthquake. Several years after the Niigata event, liquefaction countermeasures were developed and have been put in place. Therefore, no liquefaction countermeasures have been taken for the ground reclaimed prior to that time.

Figure 8 shows a quay wall of a manmade island reclaimed from Tokyo bay and the assessment result of soil liquefaction by the Northern Tokyo bay earthquake, which has been predicted to have a high probability of occurrence directly beneath the greater Tokyo area in very near future. Reclamation began in this area around 1930 and was completed about 1960. As shown in the figure, there are steel sheet pile walls with an anchorage, and the ground is composed of sandy soil of the former seabed (N values are 10 to 15) and a layer of sandy fill (N values are about 5). It is supposed that there would be thick liquefiable ground below the ground surface, and that bottoms of the steel sheet wall would not reach into the lower non-liquefiable clayey soil. If liquefaction occurs, it is likely that there would either be significant deformation of the steel sheet pile quay walls, or in the worst case that they would collapse. If they were to collapse, the reclaimed ground behind the quay walls would substantially move seaward.

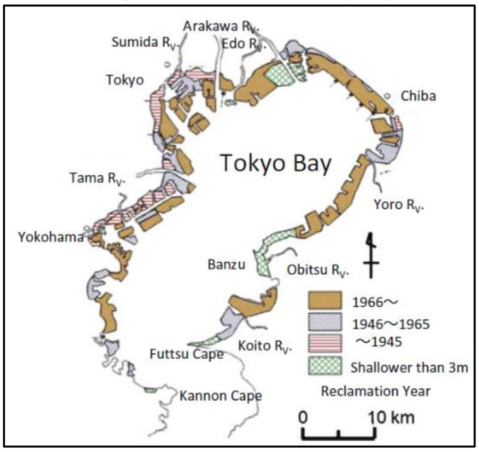


Figure 7 History of Reclamation of The Tokyo Bay [Kaizuka S (1993) Geology and water of the Tokyo Bay (in Japanese)] [4]

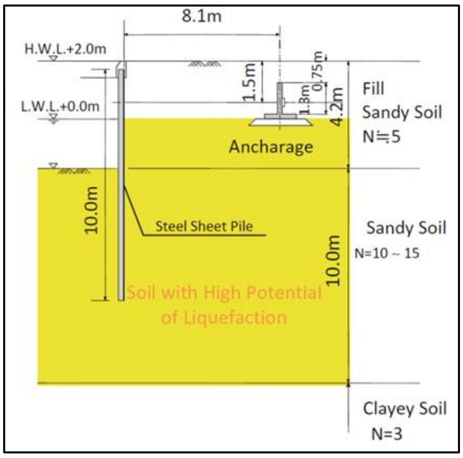


Figure 8 Quay wall of An Artificial Ground Reclaimed from The Tokyo Bay, and Assessment of Soil Liquefaction

Based on a simplified method for the prediction of the movement of quay walls and horizontal displacement of the ground [5], it is supposed that these walls would move up to 7 m seaward and that the reclaimed ground would also be displaced towards the sea, as shown in Figure 9. Thickness of the layer to be liquefied is predicted to be more than 10 m.

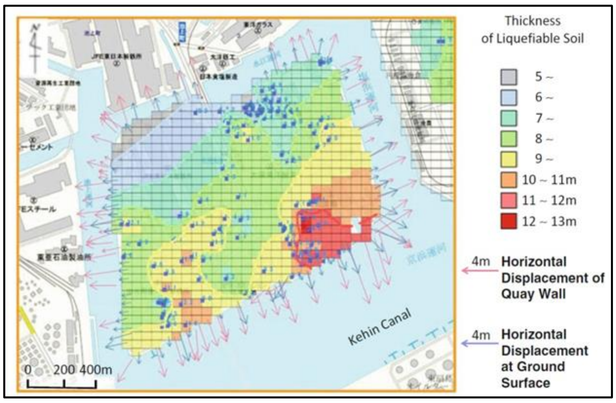


Figure 9 Assessment of Soil Liquefaction of An Artificial Island and Horizontal Displacements of The Quay Walls and The Ground

2.2 Long-period components of earthquake ground motion

Figure 10 shows examples of floating roof-type tanks for the storage of oil in an oil refinery plant in Tokyo bay. It is reported that more than 600 floating roof-type tanks have been constructed on reclaimed ground around the bay.

Figure 10 An Oil Refinery Plant Around The Tokyo Bay

Figure 11 shows earthquake ground motions and the velocity response spectra that have been predicted for coastal areas along the bay, under an assumption of continuous occurrence of Tokai and Tonankai earthquakes along the Nankai trough in the Pacific Ocean. Long period earthquake ground motions of 9–10 s in the Chiba area and 6–7 s in the Kawasaki area would be dominant. The thickness of soft surface soil in the Chiba area is about 3 km, larger than 2 km in the Kawasaki area. Based on the analysis of the sloshing vibration of the oil in tanks, it is estimated that the oil of 64 tanks, approximately a tenth of the 600 total, would overflow

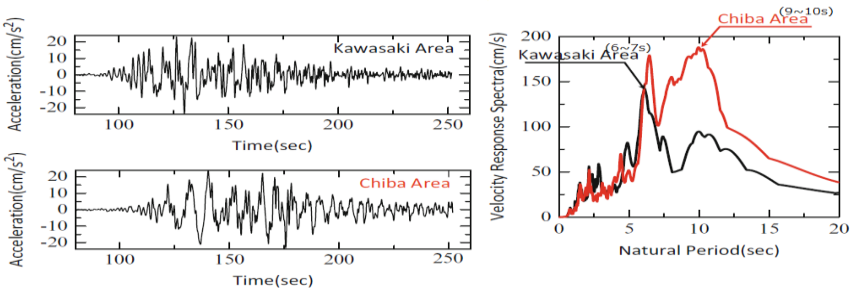


Figure 11 Earthquake Ground Motions with Long Period Component and Their Spectra in the Tokyo Bay (continuous occurrence of The Tokai and Tonankai earthquakes, by Prof. Furumura University of Tokyo).

by the sloshing vibration as shown in Table 1. It is expected that some of these incidents would involve fires, as experienced during past earthquakes.

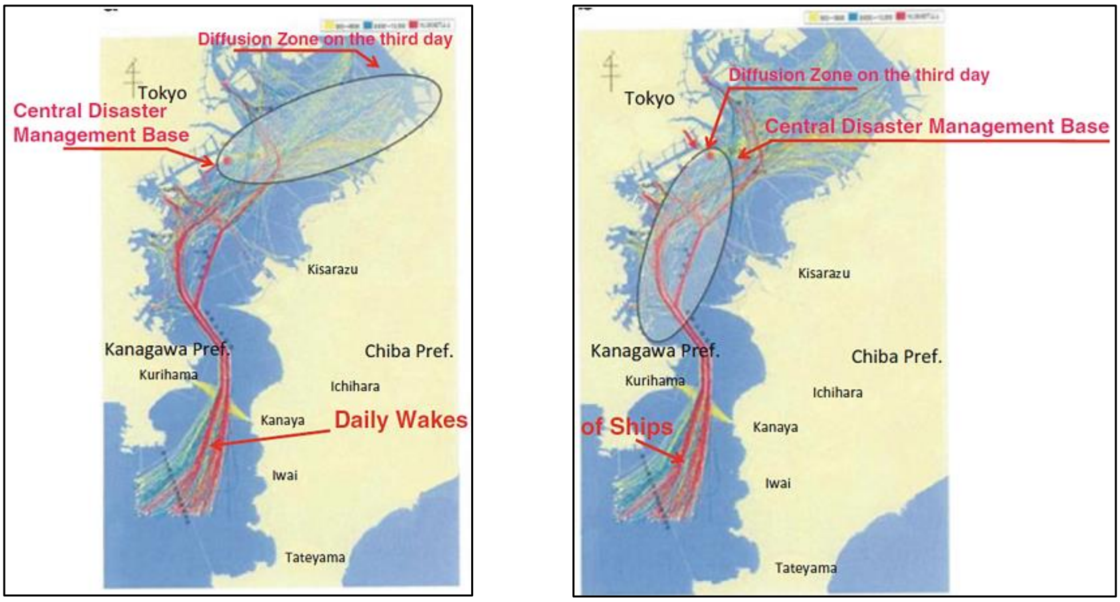
In addition to the large ground displacements induced by the lateral flow of liquefied ground, the sloshing vibration of the oil would spill a large amounts of crude and heavy oil into the Tokyo bay, and the oil would widely diffuse on the sea. It is certainly possible that this oil could be ignited, causing a large scale fire on the sea surface.

Diameter of tanks (m)	Total number of tanks	Number of overflowing tanks
~24	203	13 (6.4 %)
24–34	136	27 (19.9 %)
34–64	118	18 (15.3 %)
~60	159	6 (3.8 %)
Total	616	64 (10.4 %)

Table 1 The Number of Floating Roof-Type Tanks and of Overflowing Tanks

2.3 Simulation of diffusion of oil in the Tokyo bay

Figure 12 shows results of a simulation of the diffusion of crude oil under an assumption where 12,000 kl of crude oil spills into the Tokyo bay from the Kawasaki industrial park. In the summer season, the crude oil would reach the Chiba area in about 3 days with southwesterly winds of speed 5.0 m/s, drifting and diffusing over a wide area of the bay. In winter, the crude oil would drift toward the mouth of the bay with northwesterly winds, also diffusing over a wide area. Figure 12 also shows a chart of daily wakes of medium and large ships (thin lines in the figure), excluding fishing and leisure boats. About 200 ships navigate Tokyo bay every day. If an oil spill spreads over the sea area as shown in the figure, it would have prevented all ships from coming in or going out of the bay for safety reasons.



(a) Summer season (b) Winter season

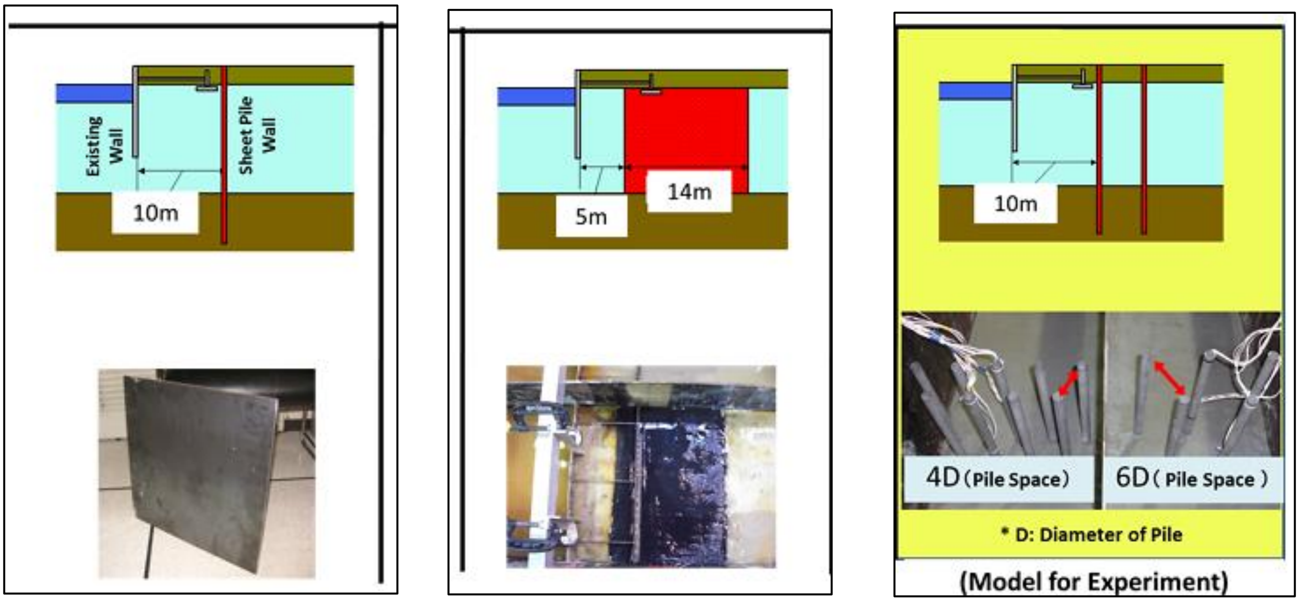
Figure 12 Diffusion of Crude Oil on The Tokyo Bay (Committee on Earthquake Damage to Bay area, Ministry of Land, infrastructure and Transport)

The Disaster Impact Study Committee for the Tokyo bay area organized by the Japanese government has estimated that collection of the spilled oil would take approximately 2 months. Fourteen thermal power plants on reclaimed land around the Tokyo bay are currently in operation, supplying at least 80 % of total electric power usage in the greater Tokyo area. The supply of liquefied natural gas and crude oil imported from overseas would be cut off in a case of the diffusion of crude oil, and this situation would result in a critical shortage of electric power in the greater Tokyo area.

3 Measures and Challenges for Earthquake and Tsunami Resilience Enhancement of Industrial Parks

3.1 Countermeasures against earthquake and tsunami [6]

In order to protect the existing quay walls and to prevent the large displacements of the reclaimed ground, various kinds of countermeasures have been proposed and developed. Figure 13 shows three typical methods for reinforcement of the existing quay walls. The first method is construction of a new steel sheet pile wall behind the existing quay walls. The second method is the soil improvement against liquefaction. The third method was developed by the authors' research group. In this method, steel pipe piles are driven in two rows with a proper interval. It is expected that the pile group prevents the flow of the liquefied soil. This method follows the landslide prevention measure by driving piles on slopes discontinuously with a proper interval. The effectiveness of these methods has been examined by centrifuge experiments.



(a) A new steel sheet wall (b) Soil improvement (c) Pile group

Figure 13 Reinforcement of Quay Walls against Soil Liquefaction and Its Caused Ground Displacement

Figure 14 shows one of the test results. The vertical axis of the figure shows the horizontal displacements on the ground surface, and the transverse axis is the distance from the existing quay walls. The experimental results clearly show the effectiveness of each countermeasure to reduce the ground displacements. Among these countermeasures, the pile group method shows a clear effectiveness for the reduction of the ground displacements, even in the case of the pile interval of several times of the pile diameter. The pile group method is effective as well as most economical among the proposed countermeasures, since construction works and costs can be largely reduced.

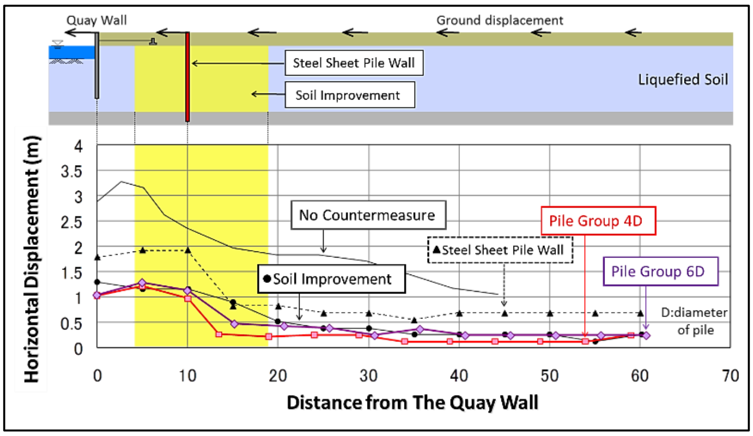
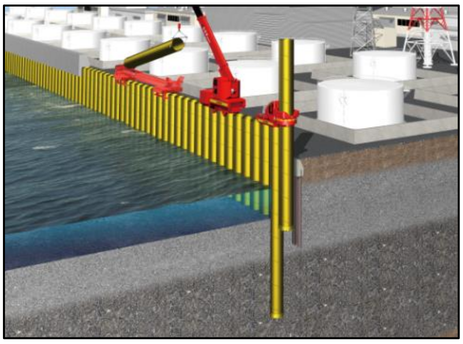
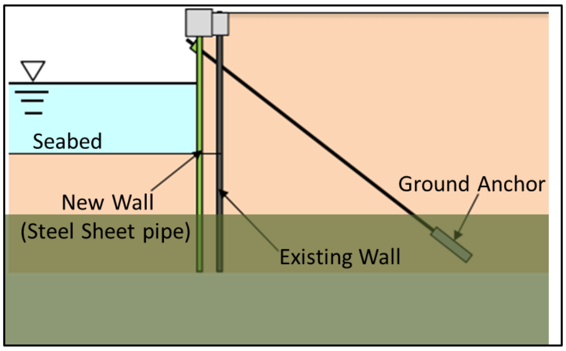


Figure 14 Effectiveness of Countermeasures for The Deduction of The Ground Displacement

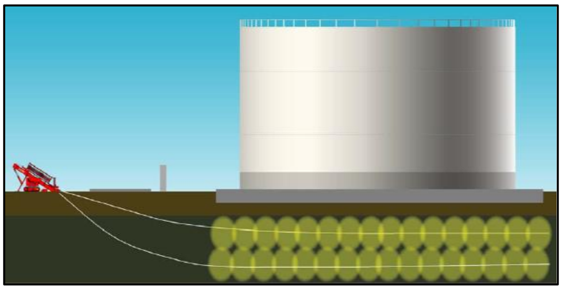
Another examples of the methods for the enhancement of the existing quay walls are shown in Figure 15. Figure (a) is steel sheet pile driving in front of the existing wall, and Figure 15(b) is a method to protect the existing wall by a ground anchor. Figure 15(c) and (d) show grouting into the foundation ground beneath the oil tanks by using bent injection pipes, and the ground water lowering method to prevent liquefaction. These methods were applied to an oil refinery plant in the Tokyo bay. In the ground water lowering method the tank site was surrounded by a flexible cut-off wall, and water level inside the wall was lowered by pumping the ground water to prevent liquefaction.



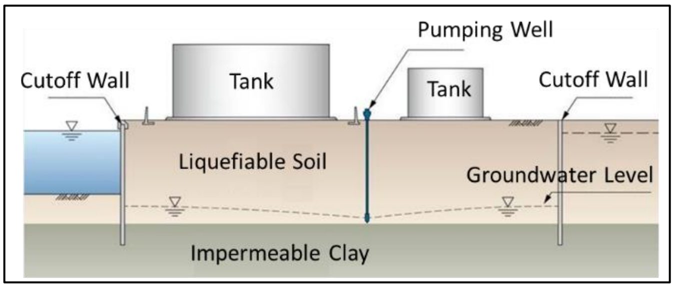
(a) Steel sheet pile wall [7]



(b) Ground anchor



(c) Grouting of foundation ground of tanks [6]



(d) Lowering of level of ground water [6]

Figure 15 Countermeasures Against Soil Liquefaction and Large Ground Displacement

3.2 Policies by the Japanese government for the enhancement of earthquake- and tsunami-resilience of infrastructure and industrial parks [8]

In 2013 the Diet of Japan enacted the fundamental law for the national land resilience against future natural disasters. The law indicates four principal policies for the national land resilience. Those are to save human lives, to prevent critical damage to functions of the nation, and safety of the people, to minimize loss of public infrastructures and people's property, and to prepare for the smooth recovery and reconstruction works after disasters.

The enhancement of earthquake- and tsunami-resilience of industrial parks in water front areas is directly related to the second principle of the fundamental law. Based on the fundamental law, the Japanese government took measures for the enhancement of earthquake- and tsunami- resilience of industrial facilities. Twenty four oil refinery plants were chosen from the areas which have high probability to be hit by large earthquakes and tsunamis in near future. The government has prepared national budget of about 16 billion yen per a year, for the financial support to the industries. The two third of the total construction cost for earthquake- and tsunami- resilience enhancement is paid by the government, and the residual is shouldered by the industries.

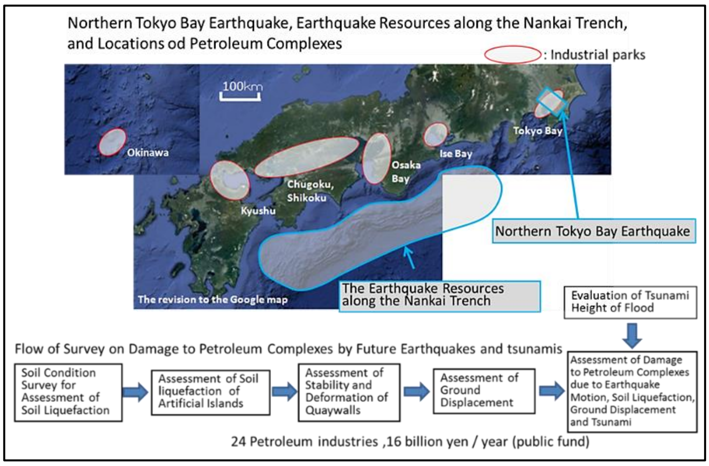


Figure 16 Survey and Practice of Earthquake- and Tsunami-Resilience Enhancement of Industrial Parks, (Policy by Ministry of Economy, Trade and Industry of The Japanese Government, 2013～)

The first step of the resilience of the industrial parks is assessment of the damage caused by the future earthquakes and tsunamis. The lower flow chart of Figure 16 shows the procedure of the survey on soil liquefaction, assessment of stability of the seawalls and ground displacements, and assessment of tsunami effects, and their caused damage to industrial parks.

4 Conclusions: Recommendations for Promotion of Earthquake and Tsunami Resilience Enhancement of Industrial Parks

For the prompt and effective enhancement of earthquake- and tsunami-resilience of industrial parks around the big bays in Japan such as Tokyo, Osaka and Ise bays, the following five recommendations have been proposed to the Japanese government and local governments by the author's research group:

1) Earthquake resilience enhancement in larger areas (whole areas of reclaimed lands as well as wide bay areas)
2) Strong leadership by the national and local governments
3) Public investment for private industrial facilities
4) Share of disaster risk information and cooperation among central and local governments, industries and local communities
5) Assessment of the impact of damage to industrial parks by future earthquakes and tsunamis on the national and world-wide economy

The first one is that, in addition of reinforcement of each industrial plant, the earthquake and tsunami resilience enhancement in larger areas such as whole areas of a manmade land including sea areas is essential, because the disaster at one plant may extend to the neighboring plants and affect the wider areas. To achieve the larger area enhancement the strong leaderships of the central and local governments are required to lead the group of the industrial companies. For the enhancement of disaster resilience of the larger areas, more public investment is also required for private properties of the industries, particularly for small industries, most of which has not enough financial bases for the reinforcement. In order to protect the maritime transportation of a canal, the reinforcement including private quay walls of industries is necessary. The fourth recommendation is risk information sharing among industries, local communities and the people for the promotion of earthquake- and tsunami-resilience of the larger areas. The assessment of the impact of a large loss of the function of industrial parks on the national economy and local societies is also necessary for the national policy making.

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◆A brief CV of Dr. Masanori Hamada

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