Upgrading Existing Levees' Seismic Resiliency with Pressed-in Double Sheet Pile Walls

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Abstract: Installing double sheet pile walls inside an earthen levee has proven to be one of the highly effective retrofit methods to enhance its structural resiliency against earthquakes and tsunamis so that it will maintain its design function even after partially damaged. Numerical analysis and model experiments conducted by researchers have verified it as long as the sheet piles are embedded in non-liquefiable soil. This method was utilized for coastal levee seismic retrofit projects in Japan and a riverine levee seismic upgrade project in Southern California where liquefiable sand and silt layers were dominant; both were designed differently.

Keywords: Liquefaction, tsunami, levee, seawall, sheet pile, press-in piling.

1 Background

A magnitude 9.0 earthquake occurred on March 11, 2011 that caused severe damage to many coastal structures in northeastern Japan. The survey report (ASCE 2013) compiled by the experts from the American Society of Civil Engineers categorizes failure modes of coastal structures observed after the Great East Japan Earthquake and Tsunami. Another major factor contributing to the damage is liquefaction of the foundation soil. Figure 1 shows a heavily damaged coastal levee in Noda in Iwate Prefecture caused by the earthquake and tsunami.

Figure 1. Heavily damaged coastal levee of Noda, Iwate Prefecture
(Tohoku Regional Bureau, Japan Ministry of Land, Infrastructure, Transport and Tourism)

There are three different types of liquefaction that contribute to a levee's failure as follows (Sasaki 2014).

1. Liquefaction of a load bearing sandy layer under a levee.
2. Liquefaction of a levee's embankment (especially in the sandy part below the ground water level in the embankment).
3. A combination of the above in case both the load bearing layer and the levee embankment are composed of sandy materials.

In the second case, as the load bearing clay layer gradually settles due to the embankment's weight, the volume of groundwater-saturated sand in the embankment increases, thus creating a more vulnerable liquefaction prone situation. It was observed at many locations of the riverine levees in the affected areas that this type of liquefaction actually caused a rather large amount of lateral spreading, settlement, and resultant multiple longitudinal cracks in the levees' crest and slopes from the earthquake (Miyatake et al. 2013).

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2 Counter Measures against the Existing Levees' Liquefaction

The following retrofitting methods have been widely utilized in order to increase the existing levees' resiliency against liquefaction through compaction of soil near the levee's toes or restraint of the underlying soil's lateral movement.

1. Soil improvement.
2. Installation of large diameter columns or use of dynamic compaction.
3. Installation of drain columns.
4. Installation of sheet piles and pipe piles.
5. Additional (thicker and heavier) embankment.

Although these methods are adopted primarily to decrease the liquefaction tendency of the load bearing layers but not to reduce liquefaction in the embankment, the levees that had received these improvements performed much better than those without them during the earthquake (Sasaki 2014). For prevention or reduction of liquefaction in the riverine levees' embankments, Nagata (2012) and Sasaki (2014) proposed the installation of drains at the toe on the river side and an additional embankment on the land side. The drains are for lowering the level of the groundwater in the embankment while the additional embankment is for increasing the strength of the embankment against lateral movement. These methods are covered in the Technical Note No. 4332 of PWRI, i.e., Public Works Research Institute of Japan (2016) for their applications in the public works projects in Japan.

3 Double Sheet Pile Walls Installed in Coastal and Riverine Levees

A temporary double sheet pile cofferdam survived the tsunami in the coastal town of Yamada in Iwate Prefecture. See Figure 2 for the cofferdam and the ruined residential and commercial district next to it. The sheet pile cofferdam was still standing upright with only partial damage in spite of the 9m high tsunami overtopping, keeping its original functions as shown in Figure 3.

Figure 2. Tsunami-survived double sheet pile cofferdam in Yamada Town, Iwate Prefecture, Japan (Japan Press-in Association, both Figures 2 and 3)

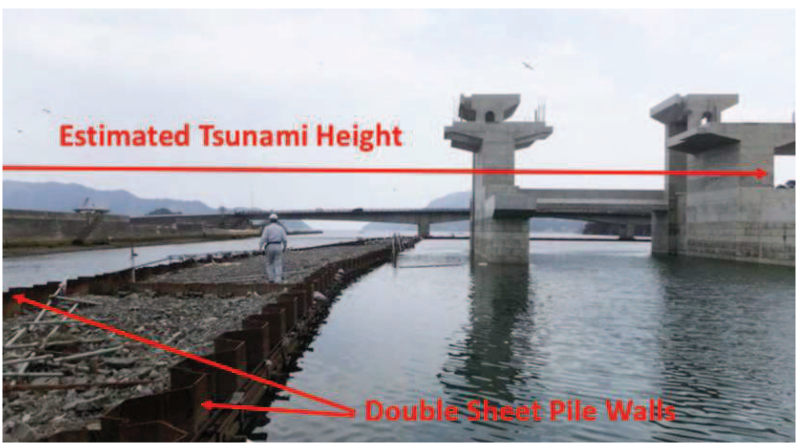

Figure 3. Almost intact double sheet pile wall cofferdam after 9m-high tsunami overtopping

The primary reason for the structure's ability to maintain a high level of resiliency against the strong vertical and lateral forces was that the sheet piles were driven into a non-liquefiable soil layer and the double sheet pile walls were connected to each other with inner bulkhead walls and tie-rods (Otsushi et al. 2015). Since then, the earthen levees' retrofitting with double sheet pile walls has been studied with numerical modeling and physical experiments by various university, government, and corporate researchers primarily in Japan.

Otsushi et al. (2011) verified through a model experiment that double sheet pile walls embedded in a non-liquefiable layer reduces settlement in the soil sandwiched between the walls and maintains the original height of the levee with the sheet piles. Nakayama et al. (2014) verified with numerical analyses that a more enhanced structural resiliency of levees could be achieved with double sheet pile walls and a pipe pile wall installed inside them against a tsunami's repeated overtopping. Mitobe et al. (2014) proved through model experiments that a reinforced levee with double sheet pile walls will maintain its function even after severe scour caused by a tsunami's overtopping. Otsushi et al. (2015) analyzed the combined effect of a strong earthquake and subsequent tsunami on the subject structure with numerical and experimental analyses, proving its substantially improved resiliency. More recently, Fujiwara (2017) wrote his doctoral dissertation on the performance of the double sheet pile wall levee structure through numerical analysis and model experiments with wider ranges of parameters, reassuring the structure's high level of reliability even in the case of sequentially occurring strong quakes plus subsequent massive tsunamis. Additionally, Kochi University et al. (2016) published a design guideline for a levee's retrofitting with double sheet pile walls and a pipe pile wall. Figure 4 shows the concept as to how an earthen levee retrofitted with double sheet pile walls endures the forces from a strong earthquake and tsunami and maintains its function even with partial damage.

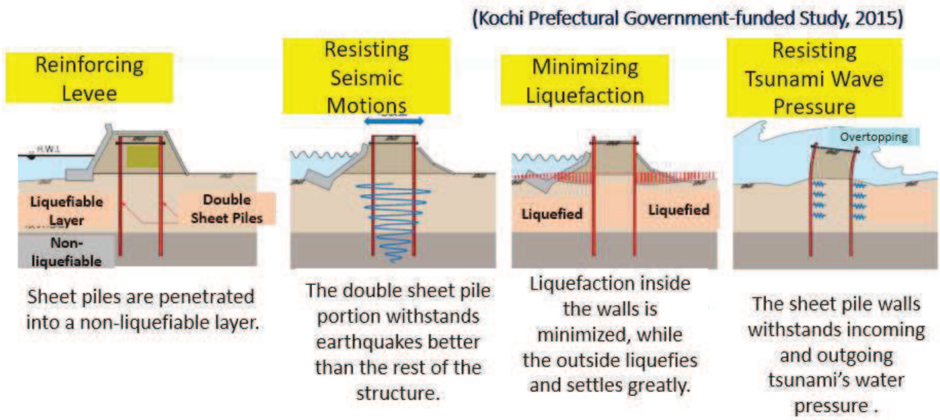

Figure 4. Concept of double sheet pile wall levee withstanding earthquake-induced liquefaction and tsunami

4 Kochi Coastal Levee Retrofit Project in Japan

The Japanese government's infrastructure department and Kochi prefectural government have been retrofitting existing coastal levees on a 21.9km long section of Kochi Coast, some 800km southwest of Tokyo. There is a major offshore fault running parallel to the coast that has been causing strong seismicity and tsunami activity which is expected to repeat in the near future. The existing coastal levee as the first line of defense against a tsunami was built decades ago and was found to be highly prone to liquefaction at many locations due to its sandy foundation soil as well as sand used for building the embankment. Where cobbles were found in the sheet piles' alignment in the lower portion of the embankment as shown in Figure 5, commonly used vibratory hammers would not have worked without large predrilling operations. Instead, press-in piling with an auger attachment was utilized to install sheet piles through the hard layer without predrilling. Note that the lower sections of the sheet piles were embedded in the non-liquefiable lower soil layer. See Figure 6 for construction of the pressed-in double sheet pile walls. Press-in machines only emit low noise and extremely low vibration (White et al. 2002). Multiple pile drivers were deployed to meet the accelerated construction schedule without disturbing local residents or damaging the existing structures, thanks to the environmentally friendly feature of press-in piling. Tie-rods were later installed to connect the sheet pile walls. A concrete capping and hand rails were placed on top thereafter. This project was the first major application of double sheet pile walls to retrofit existing earthen levees in Japan. Additionally, much wider levee sections utilized a pipe pile wall, which was also installed with the press-in method. There are other similar projects at the planning stage based on the experience gained from this.

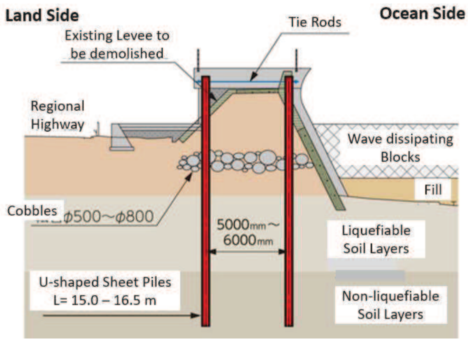

Figure 5. Typical cross section of Kochi Coastal Levee Retrofit Project with double sheet pile walls

Figure 6. Press-in work of sheet piles into the existing levee at multiple sections

5 East Garden Grove – Wintersburg Channel Levee Upgrade Project in California, U.S.A.

The East Garden Grove – Wintersburg Channel is part of the Orange County Flood Control District in California, U.S.A. and is being operated and maintained by Orange County Public Works. The channel's levees were made mainly of native soil back in the 1960's. The agency has started to retrofit the levee in phases first to take care of emergency repair in response to previous flood damage and subsequently to enhance its seismic resiliency in sections due to its proximity to active fault zones and dense and residential areas. Phase 2 for a total of 1,650m levee length of the project utilized deep soil cement mix columns (DSCM) sandwiched within double sheet pile walls to meet the seismic requirements for neighboring homes for fear of potential liquefaction of the levee's embankment. The length of the sheet piles was limited to 13.7 meters in order not to disturb the groundwater flow in the aquifer below the channel. Disruption of ground water would result in settlement or flooding of the neighboring lots along the levee. Soil improvement was necessary inside the sheet pile walls because the sheet piles alone would not provide sufficient resiliency against potential liquefaction due to their limited lengths. This new design concept was formed after reviewing traditional but unapplicable design guidelines; later verified by independent consultants and also reviewed by the U.S. Army Corps of Engineers. The group of the DSCM columns was designed to form an impermeable barrier to mitigate potential liquefaction between the sheet pile walls to compensate for lack of self-sufficient embedment of sheet piles and act as monolithic soil-filled compression rings against strong seismicity. See Figures 7 and 8 for a typical cross section and a plan view of the improved levee with double sheet pile walls and hexagonal arrangements of DSCM columns. The design would also circumvent the types of levee failure caused by Hurricane Katrina (cut-off walls deflected and pushed over by flood water and uplift due to weak materials in levees and their underlying soil layers, USACE, EC 1110-2-6067, 2010). Selection of sheet pile walls was designed with five different models in non-homogenous soil conditions due to the seismic fault, lenticular intermingling soil strata, and lenses of organic materials. The design procedures and manuals of the U.S. Army Corps of Engineers were referred to and utilized to verify their adequacy (Fayad et al. 2015). The sheet piles were pressed in due to the proximity to the nearby homes and concern about the levee's potential liquefaction by vibratory pile driving (Takuma 2017). See Figure 9 for the installed double sheet pile walls prior to the DSCM column work.

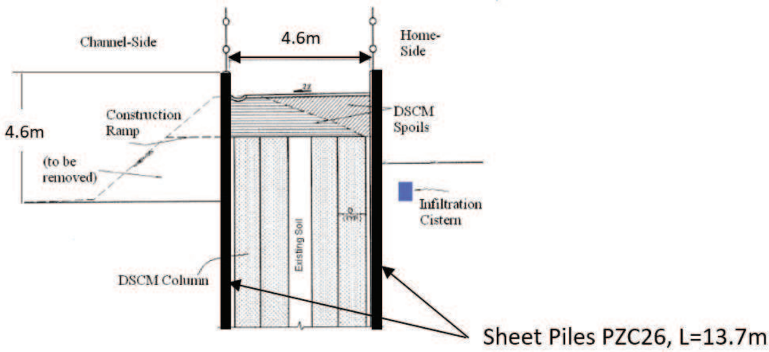

Figure 7. Typical cross section of the upgraded levee

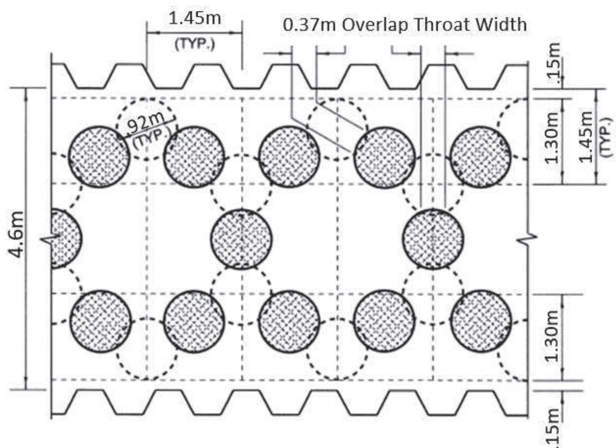

Figure 8. Typical plan view of upgraded levee with double sheet pile walls and DSCM columns

Figure 9. Completed double sheet pile walls

It should be also noted that a 120-m long section of the levee where an active tectonic slip zone is located installed a single sheet pile wall with extra T-shape joints at every other pair of sheet piles. This arrangement was made to allow the sheet pile wall to horizontally deflect and expand without breaking apart at the interlocks according to the degree of the fault's gradual movement thanks to these extra joints during its design life span of 75 years.

6 Conclusions

Many earthen levees located in a seismic zone are susceptible to liquefaction, especially those made of sandy materials and those underlain by a sand layer. Installing double sheet pile walls in these levees is a reliable retrofit method among others to make the levee system resilient against not only strong earthquakes but also against a subsequent tsunami's or flood water's overtopping. Sheet piles can be accurately installed even through gravel and cobbles without a high level of noise or vibration if they are pressed in. A combination of deep soil cement mix columns sandwiched with double sheet pile walls provides solid liquefaction-proof levee structures without disturbing the flow and the level of ground water under and near the levee. The author hopes that the two different design approaches discussed herein will be further refined and more widely applied to existing levees' seismic upgrades with double sheet pile walls in the future.

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References

Ewing, L., Takahashi, S., and Petroff, C. (2013). Tohoku, Japan, earthquake and tsunami of 2011, survey of coastal structure. *American Society of Civil Engineers*, 44-63.

Fayad, A.S., Takuma, T., and Kambe, S. (2015). Levee repair and upgrade by dual sheet pile walls and accordion sheet pile wall. *Proceedings of 2015 Annual Conference of Deep Foundations Institute.*

Fujiwara, K. (2017). Reinforcement method for coastal dyke using double sheet-pile against large Earthquake, *Gifu University Institutional Repository,* http://hdl.handle.net/20.500.12099/56173 (in Japanese)

Kochi University, Giken Ltd., and Nippon Steel and Sumitomo Metal (2016). *Design Guidelines for Levee Retrofit with Double Sheet Piles and Pipe Piles Against Earthquake and Tsunami* (in Japanese).

Mitobe, Y., Otsushi, K., Kurosawa, T., Adityawan, M.B., Roh, M., and Tanaka, H. (2014). Effects of embankment reinforcement with steel sheet piles against tsunami overflow. *Journal of Japan Society of Civil Engineers, Ser., B2, Coastal Engineering,* 70(2), 976-980 (in Japanese).

Miyatake, K., Nakayama, O., and Yanahata, T. (2013). Characteristics of riverine levee damage caused by Great East Japan Earthquake, *Japan Institute of Country-ology and Engineering Report,* 23, July, 2013, 16-20 (in Japanese).

Nagata, H. and Sasaki, T. (2012). Research on aseismic measures for riverine levees. *Proc., Ministry of Infrastructure, Land, Transport and Tourism, Annual Technical Research Conference 2012,* www.mlit.go.jp/chosahokoku/h24giken/program/kadai/pdf/shitei/shi2-03.pdf (in Japanese).

Nakayama, T., Furuichi, H., Hara, T., and Nishi, T. (2014). Verification of stability against tsunami of levee including double sheet pile wall based on numerical simulations. *Proc., Japan Geotechnical 49th Annual Conference* (in Japanese).

Otsushi, K., Koseki, J., Kaneko, M., Tanaka, H., Nagao, N. (2011). Experimental study on reinforcement method of levees by sheet-pile. *Japanese Geotechnical Journal*, 6(1), 1-14.

Otsushi, K., Kurosawa T., Fujiwara, K., Toda, K., Yoshihara, K., Okuda, Y., Nishibe, K., and Kurosaki, K. (2015). Solution technology of coastal dike and tide barrier against large earthquake and tsunami run up. *Nippon Steel Sumitomo Metal Technical Journal,* 403, 70-77 (in Japanese).

Sasaki, T. (2014). Verification of effectiveness of anti-liquefaction countermeasures on riverine levees and research on further enhancement, www.nilim.go.jp/lab/bbg/saigai/h23tohoku/houkoku4/happyou/140319-09.pdf (in Japanese).

Takuma, T. (2017). Riverine levee upgrades against liquefaction and seismic impact with double sheet pile walls and deep soil cement mix columns. *Proceedings of GeoRisk 2017 Conference,* ASCE.

White, D., Finlay, T., Bolton, M., and Bearss, G. (2002). Press-in piling: ground vibration and noise during piling installation, *ASCE Special Publication, 116*, 363-371.