Title

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Publication Date

2012-09-24

Groundwater Level Evaluation for River Flood Control Levees and its Effect on Seismic Performance

15 WCEE
LISBOA 2012

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SUMMARY:
We are working towards developing risk assessment tools for levees to identify conditions that correlate with ground failure rates. Our initial data set is from the 2007 M_w6.6 Niigata Chuetsu-oki earthquake in Japan. Liquefaction-induced ground failure is a major source of levee damage in this case, so groundwater elevation is expected to be a critical factor affecting damage locations. What we seek is the water level in or beneath the levees themselves along the full length of the study region, which encompasses approximately 110km of levees. The available data includes river water levels (generally below the levee toe) and groundwater levels within levees measured from boreholes. Our approach, which is applied along the full length of the study region, is first to establish the river water elevation (RWE) both at the time of the earthquake and at the time of subsurface exploration in the levees, and second to establish the differential between levee ground water elevation (LGWE) and RWE at the exploration time. Each step presents challenges due to sparse and incomplete data. Once the above relations are established, the LGWE is taken as the sum of RWE on the earthquake date and the differential. Comparing the result to damage reports indicates that levee segments with LGWE higher than the levee base elevation have approximately nine times higher damage rates than those with deeper ground water.

Keywords: Levee, Groundwater elevation, Liquefaction, 2007 Niigata Chuetsu-oki earthquake

1. INTRODUCTION

A levee is a natural or artificial embankment that provides flood protection adjacent to rivers or coastal areas. Because levees are generally constructed on soft soils, seismic hazards are generally driven by ground failure involving weak and potentially liquefiable soils in the foundations and in the levees themselves.

Historically, levees were often constructed in a haphazard manner without proper engineering, for example in the San Francisco Bay-Delta region and in Japan prior to the 1995 Kobe earthquake (CDWR, 2009; Sugita and Tamura, 2008). More recently, levee design standards have been established which consider seismic demands (CDWR, 2009; Sugita and Tamura, 2008), but the principal problem remains the substantial levee networks already in place that were not properly engineered (CDWR, 2009).

Modern standards for engineering evaluation of levees involve subsurface exploration, development of cross sections, analysis of seismic demands within the levee and foundation using finite element analysis, and evaluation of liquefaction and landslide potential based on the outcome of those analyses (CDWR, 2011; Sugita and Tamura, 2008). There are two potential problems with this approach when applied to a broad levee network. First, such analyses are very labor intensive and costly. As such, screening tools to identify the most critical conditions requiring detailed analyses have the potential to be a useful component in the risk assessment toolbox. Second, researchers tend to focus on case histories that exhibited poor performance rather than good performance, thereby biasing empirical observations and making traditional methods inherently conservative. Hence, calibration against field observations of entire levee systems, including both good and poor performance, is important. For both of these reasons, we have undertaken a large, multi-agency project to compile and analyze case history data of levee performance and to leverage the lessons learned into improved risk assessment and relatively detailed analysis tools. Agencies contributing to this effort include the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan, the California Department of Water Resources (CDWR), the U.S. Army Corps of Engineers (USACE), the University of California (Berkeley (UCB) and Los Angeles (UCLA) campuses), and the University of Tokushima in Japan.

In this article, we describe procedures for estimating groundwater elevation at the time of an earthquake based on (*i*) measurements of river water elevation (RWE) from streamgauge stations at the time of the earthquake, (*ii*) measurements of levee groundwater elevation (LGWE) at the time of a geotechnical boring, and (*iii*) RWE at the time of the boring. A key assumption is that the RWE is directly related to LGWE since levees lie adjacent to the river, although we recognize that LGWE may also be affected by land-side agricultural practices. We anticipate that groundwater level will strongly influence ground failure rates along levees because liquefaction is a principal cause of ground failure. The process is illustrated using data from Shinano River flood control levees (Fig. 1), which were strongly shaken by the 2007 Niigata-ken Chuetsu-oki earthquake in Japan. This event was selected because (*i*) levee performance was well documented by staff of the MLIT and the Niigata Prefectural Office agencies (NPO) in Japan (who walked the full length of the levees in the effected regions), (*ii*) the level of ground shaking was strong enough to cause levee damage (maximum recorded PGA > 0.9g) on the surface projection of the fault rupture and low enough further upstream to leave levees undamaged (thereby bracketing the full response range), and (*iii*) significant geotechnical data has been compiled for the region as part of engineering studies to support repair work. We have previously presented ground motion estimates for this levee network in Kwak et al. (2012).

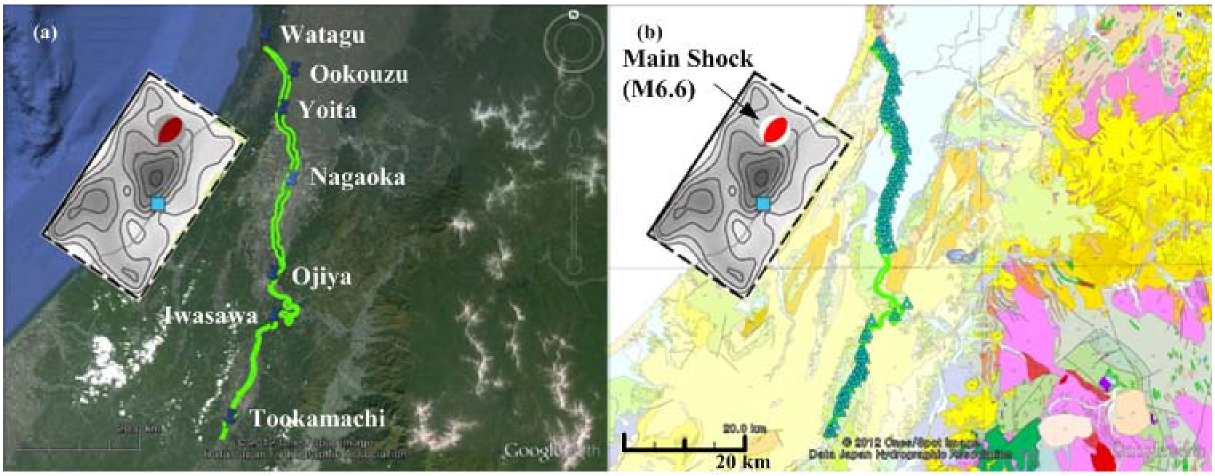

Figure 1. (a) Levees in study region (green line) and locations of streamgauge stations (blue pins), and (b) 1:200,000 scale geology map (GSJ, 2009) and locations of boreholes (blue triangle). Levees are present along the river up to 80km upstream from the outlet. Geological conditions beneath the levees include Holocene sediments (light blue color in geology map) in downstream area and late Pleistocene lower terrace deposits (light green color in geology map) in upstream area. The epicenter (beach-ball) and fault rupture plane (black rectangular) are from Miyake et al. (2010).

2. DATA SOURCES

We collected river water elevations (RWEs) from seven streamgauge stations (locations in Fig. 1a), which are operated by MLIT Water Information System (MLIT, 2012). These RWE values are available daily; we are particularly interested in values on the earthquake date and date of subsurface exploration (boring date). For reasons explained in Section 3, we also utilize data providing RWE at 500m intervals during a flood event on October 21, 2004.

Following the 2004 Niigata Chuetsu earthquake, the MLIT Shinano River Office performed geotechnical investigations along the levees. As shown in Fig. 1b, 305 borings are available along the Shinano River up to 80km upstream from the outlet. Groups of three borings were typically drilled at a given levee section near the crest, river-side, and land-side slope or berm. Cross sections drawn from the borehole data show borehole water table and subsurface soil conditions, as illustrated in Fig. 2. We utilize this data to extract levee ground water elevations (LGWE), as described in Section 4, and the levee base elevation (LBE).

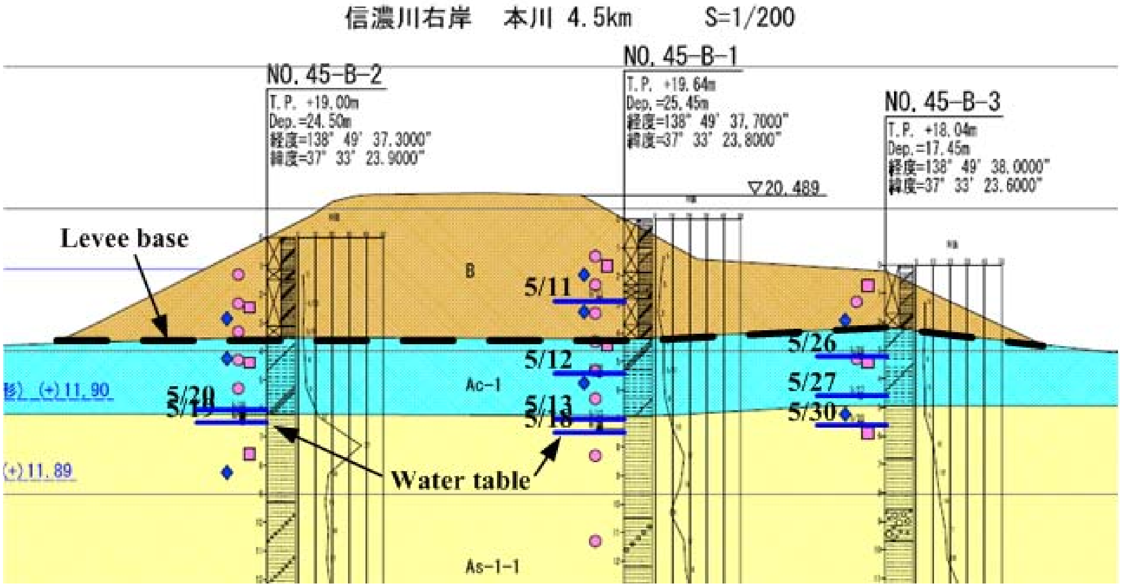

Figure 2. Example cross section through levee showing levee base and levee ground water elevations (LGWE) from boreholes on various dates.

MLIT reports (MLIT, 2007) describe the earthquake-induced damage to levees. Damage was quantified by measuring crack depth and width, the amount of slip (offsets across cracks), and the amount of relative settlement between damaged and undamaged sections of levee. There are various types of damage, but crack depth and crest subsidence are common parameters to describe damage severity. We classify damage in five levels from zero to four as shown in Table 1 for 50 m (in length) levee segments up to 80km upstream from the outlet. The total number of levee segments including those on the left- and right-sides of the river (when looking downstream), is 2145. Of those, 108 segments exhibited damage level 1 or higher (hence, overall damage rate is 5.0%). Damage level 4 was not detected. In Section 5, we evaluate damage rate by analyzing damaged segments with respect to LGWE.

Table 1. Levee damage classification

Damage Level	Crack Depth (cm)	Subsidence (cm)	Description
0			No damage reported
1	< 50	< 10	Slight damage, surface manifestation of liquefaction
2	50~100	10~30	Moderate damage
3	100~300	30~100	Severe damage
4	> 300	> 100	Levee collapse

The study region is well instrumented with ground motion accelerometers having variable site conditions. Kwak et al. (2012) describe a procedure for mapping ground motion intensity measures within the study region which preserves the spatial variation in ground motion levels associated with variable source, path, and site effects. The results of that work indicate that peak accelerations have relatively little variation along the levee alignment (approximately 0.15 to 0.27g), which occurs in large part because the Shinano River is nearly parallel to the fault strike, as shown in Fig. 1.

3. RIVER WATER ELEVATION

River water elevations (RWEs) are obtained from streamgauage stations. RWEs are measured hourly and daily; we utilize the day-based database. We sample this database on the earthquake date, the date of subsurface exploration, and the date of the relatively detailed flood survey (Oct 21 2004) mentioned in Section 2. As shown in Fig. 1a, there are seven stations along the study region, which is too sparse spatially to provide accurate RWEs for each 50m levee segment considered in this study.

To guide spatial interpolation between streamgauge stations, we utilize the detailed RWEs measured at approximately 500m intervals during the Oct 21 2004 flood event. Fig. 3 shows the RWEs on Oct 21 2004 from the seven streamgauges, linear interpolation between streamgauges, and the detailed surveys at 500m intervals. The streamguage data matches that from the detailed surveys at the respective stations, but linear interpolation is seen to provide a poor fit to the data trends between stations, particularly in the upstream region (beyond 60km).

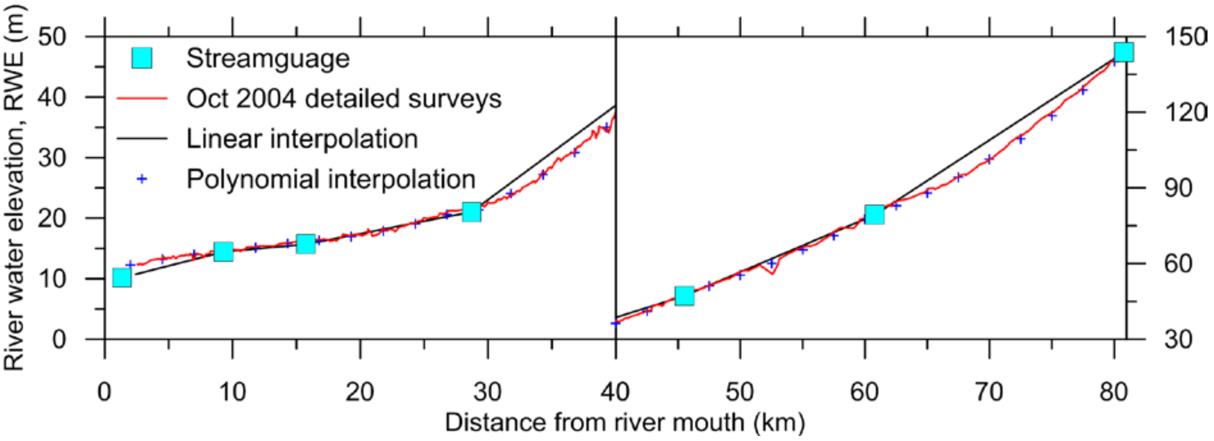

Figure 3. RWEs along the Shinano River on Oct 21, 2004. RWEs at streamgauges are consistent with those from detailed surveys on this date. The trend is misfit by linear interpolation but captured by polynomial interpolation.

To resolve the RWE misfits, we apply non-linear interpolation established by a non-linear regression between linear interpolation residuals ($R = RWE_{data} - RWE_{lin\_interp}$) and distance from river mouth (D) as follows:

$$R_i = C_{0i} + C_{1i} D + C_{2i} D^2, \quad if \;\; a_i \leq D < b_i \tag{3.1}$$

where R_i is residual for levee interval i, C_{0i}, C_{1i}, and C_{2i} are regression parameters for interval i, and a_i and b_i are minimum and maximum distances for interval i. The coefficients are given in Table 2. The residuals and model fits are shown in Fig. 4.

Table 2. Regression parameters for RWE residuals for each river interval

Interval, *i*	*a*	*b*	C_0	C_1	C_2
1	1.35	9.28	1.985	-0.092	-0.011
2	9.28	15.75	0.476	-0.104	0.007
3	15.75	28.7	10.855	-1.036	0.024
4	28.7	45.5	52.543	-3.014	0.041
5	45.5	60.8	116.264	-4.401	0.041
6	60.8	80.8	406.012	-11.651	0.082

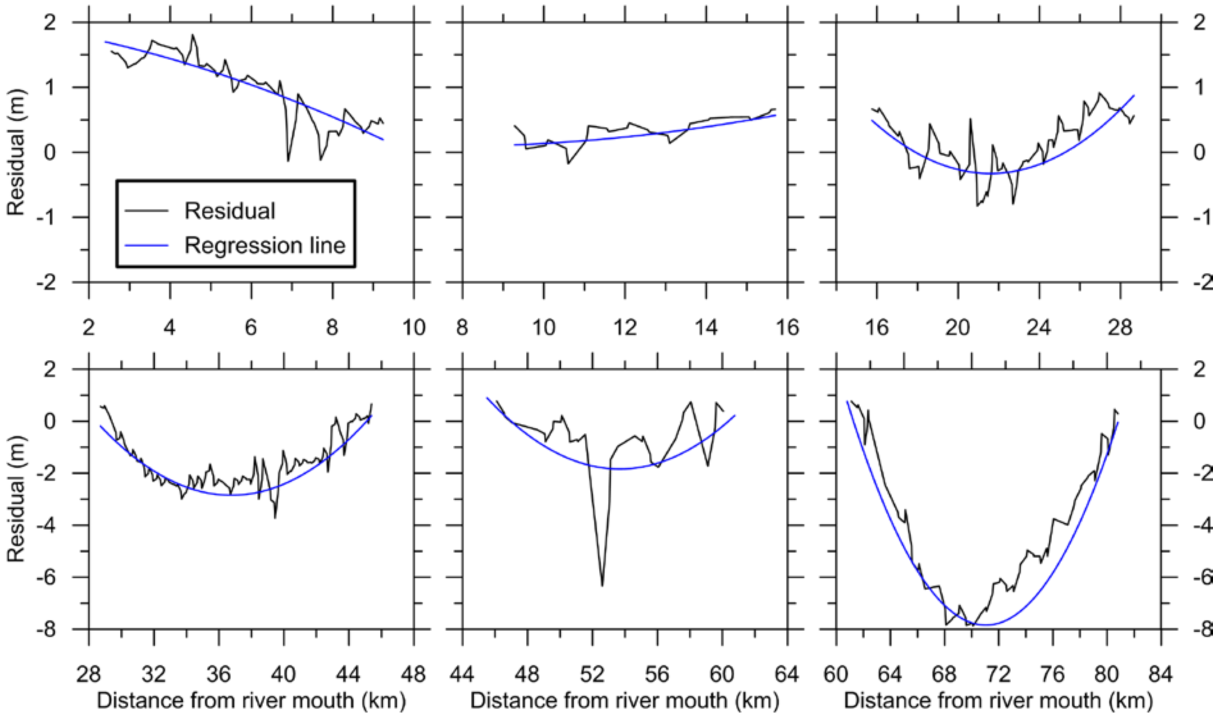

Figure 4. Residuals and regression line for each interval between river elevation measuring stations.

The blue plus symbols in Fig. 3 show non-linearly interpolated river elevations obtained by adding the residual model in Eqn. (3.1) to linearly interpolated river elevations. The results match the relatively detailed RWE measurements. For application on other dates (such as the earthquake date or date of subsurface exploration), we obtain RWE as the sum of linearly interpolated RWE from strain gauges and the model from Eqn. (3.1).

4. LEVEE GROUNDWATER ELEVATION

Our approach to establish levee ground water elevation (LGWE) is to use available borehole data to evaluate the differential between LGWE and RWE at the time of subsurface exploration. This differential is then added to the RWE at the time of the earthquake to estimate LGWE on the earthquake date. This procedure is intended to account for groundwater fluctuations in time from various sources such as precipitation and irrigation, which should be reflected in the RWE. However, we recognize this assumption may not always hold, such as if irrigation practices do not affect RWE. In this section, we describe how LGWE data was obtained from boreholes and procedures for analysis of the LGWE-RWE differential along the river length.

As shown in Fig. 2, LGWE were measured in boreholes performed at various locations along the levees, as shown in Fig. 1b. The measurement of water levels in boreholes is sensitive to the method of drilling. In the case of auger methods, water levels typically rise with time as the boreholes fill to the water table elevation. In the case of rotary wash method, water levels typically drop with time as the drilling fluid flows from the borehole until the water table elevation is reached. It is not clear from the MLIT boring logs and accompanying reports when drilling fluid was used. However, our general interpretation is that auger methods were used until ground water was encountered, after which drilling fluid was introduced to maintain hole stability. In most cases ground water elevations drop with time (such as in Fig. 2), but there are cases of ground water rise, particularly in the alluvial sections just upstream of the river mouth.

We set three criteria to screen water elevations from boreholes as follows:

1. Water elevations should be measured following the completion of drilling.
2. Water elevation change between successive measurements in time should be less than 1m (LGWE measurements are at one day intervals). When only a single measurement in time was made, it is considered only if the measurement was taken at least one day following the completion of drilling.
3. The last (in time) LGWE is selected among multi-measurements within a borehole.

The objective of these screening criteria is to obtain stable water elevations, which may include perched ground water.

LGWE-RWE differentials are computed for each levee cross-section along the river having boreholes. Fig. 5 shows all data points (black dots) and elevation differentials obtained by screening the LGWE data as described above. The polynomial fit was obtained by fitting the screened data versus distance from river mouth. The sparse data from 40 to 70km occurs because the river has carved a natural deep channel in stiff soil/rock, so levees are not present. The screened data are near the bottom of the observations between 70 to 80km because LGWE was dropping with time following drilling, whereas between 10 and 40km the screened data are more near the middle of range. Close to the river mouth the principal soil conditions are silt and clay with sand interlayers (Fig. 1b), whereas at greater distance the major soil conditions are gravel and rock. LGWEs may therefore be more reliable at the further upstream locations due to higher permeability.

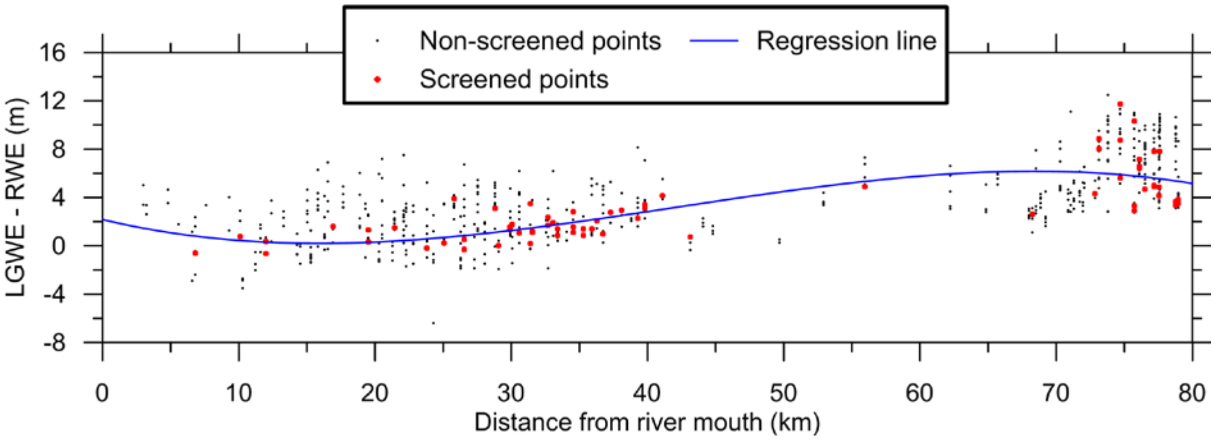

Figure 5. LGWE-RWE differentials along river length. Regression fit is applied to screened data and is 3rd order polynomial.

In areas near the river mouth, the river is broad, the surrounding terrain is relatively flat, and the flow velocity is slow. It is not surprising that under such conditions the LGWE-RWE differential would be nearly zero, as observed in Fig. 5. The positive LGWE-RWE differential in upstream areas results from the relatively narrow river width and high flow velocity, which carves a deeper river channel.

5. INTERPRETATION

Following the procedure described in Section 4, RWEs on the earthquake date (July 16, 2007) were estimated using the methodology described in Section 3. LGWE on that date was then computed as the sum of RWE and the differential shown in Fig. 5. Fig. 6 shows the RWE, LGWE, and levee base elevations (LBE) for the left and right levees (from the downstream-view perspective). LBEs are generally lower than LGWEs at distances less than 20km, and are generally higher at distances larger than 20km.

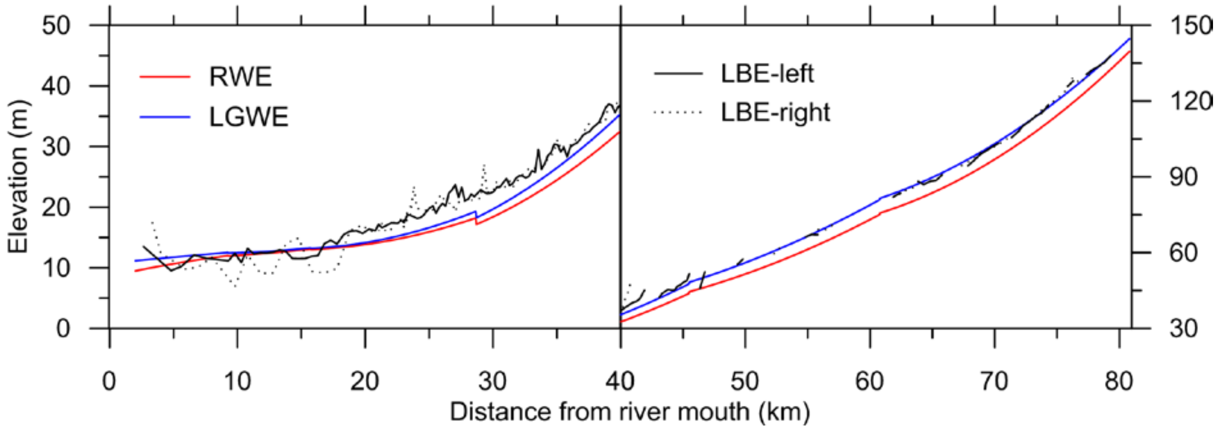

Figure 6. Levee base elevation (LBE) as compared to RWE and LGWE on earthquake date (July 16, 2007).

To investigate the effect of water level on ground failure in levees, in Fig. 7a we plot the LGWE-LBE differential against distance from river mouth. Each point represents a 50m levee segment, and damaged sections (Damage Level from Table 1 ≥ 1) from the MLIT (2007) are marked. The damaged sections appear mostly within 12km of the river mouth at sections with positive LGWE-LBE differentials, indicating that the water level is above the levee base. Fig. 7b shows the cumulative damage rate across all levee segments relative to the LGWE-LBE differential for Damage Levels 1-3. The abrupt change at zero differential is from a 0.7% cumulative damage rate at 0m to approximately 4.6% at 2m. Expressed a different way, the ratio of damaged levee segments to number of levee segments with LGWE < LBE is 1.2%; whereas the corresponding percentage is 10.8% for LGWE > LBE (change is a factor of nine). The large increase in damage rates indicates the importance of liquefaction as a ground failure mechanism, which can only occur in saturating soil materials.

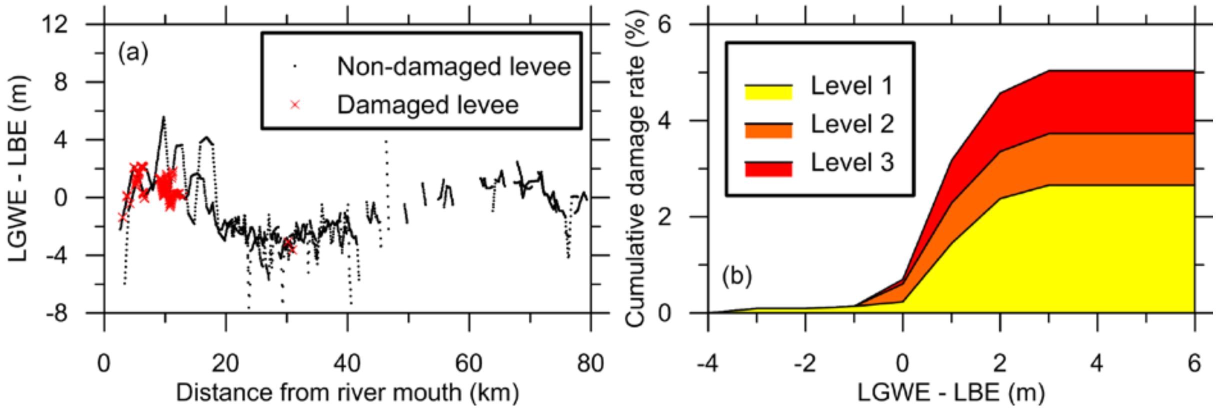

Figure 7. (a) The difference between GW elevation and levee base along with distance from river mouth, and (b) cumulative damage rate along with GW elevation minus levee base. Damage rate are calculated by damaged levee segments over total levee segments. The cumulative damage rate increase stiffly when GW elevation passes over levee base.

6. CONCLUSION

In order to evaluate the effects of ground water elevation on damage rates in levees subjected to strong earthquake ground motions in west coast of Japan, we have evaluated levee groundwater elevations (LGWE) at the time of the earthquake from river water elevations (RWE) on the earthquake date and LGWE-RWE differentials evaluated on the date of borehole explorations performed along the levee alignments. We analyze damage rates by comparing LGWE to levee base elevation (LBE).

RWEs were obtained using data from seven streamgauge stations, which was interpolated in space and time. Spatial interpolation was aided by a densely sampled survey of river elevation at a particular time. LGWEs at the time of borehole drilling were estimated from borehole water elevations, which were carefully screened to evaluate as accurately as possible natural groundwater elevations. LBEs were provided from documentation by MLIT (2007).

We find high damage rates when the LGWE elevation is higher than LBE. When this differential is negative (water below levee base), we find a damage rate of < 1.2%. When this differential is significantly positive, damage rates increase by approximately a factor of nine. The range of ground motion is relatively modest over the study area, although refinements in these damage rates are likely possible by conditioning the data both on groundwater level and ground motion level. Nonetheless, the data suggest that liquefaction, which requires saturated soils, is likely the driving mechanism of the observed ground failures at the levee sites. Additional factors such as levee height and foundation soil conditions are being investigated in ongoing research.

ACKNOWLEDGEMENT

The study was supported by the California Department of Water and Resource (CDWR) with contract number 442591-SJ-18583. The authors acknowledge data providers, MLIT, Shinanogawa River Office, NPO, and GSJ. The authors also thank our collaborators Raymond B. Seed and Juan M. Pestana at the University of California at Berkeley (UCB), Ariya Blakrishnan at CDWR, Leslie F. Harder, Jr. at HDR Inc., and Vlad G. Perlea at U.S. Army Corps of Engineers (USACE).

REFERENCES

California Department of Water Resources (CDWR). (2009). Delta Risk Management Strategy, accessed from: http://www.water.ca.gov/floodmgmt/dsmo/sab/drmsp/ (last accessed December 2011).

CDWR. (2011). Levee Evaluation Program, accessed from: http://www.water.ca.gov/levees/evaluation/ (last accessed December 2011).

Geological Survey of Japan (GSJ), AIST (ed.) (2009). Seamless digital geological map of Japan 1: 200,000. Dec 15, 2009 version. Research Information Database DB084, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology.

Kwak, D.Y., Mikami, A., Brandenberg, S.J., and Stewart, J.P. (2012). Ground Motion Estimation for Evaluation of Levee Performance in Past Earthquakes. *9th International Conference on Urban Earthquake Engineering/ 4th Asia Conference on Earthquake Engineering.*

Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (2012). Water Information System, accessed from: http://www1.river.go.jp (last accessed April 2012, in Japanese).

MLIT. (2007). Report of Damage Survery and Estimation of the Shinano River, in Japanese.

Miyake, H., Koketsu, K., Hikima, K., Shinohara, M., and Kanazawa, T. (2010). Source Fault of the 2007 Chuetsu-oki, Japan, Earthquake. *Bulletin of the Seismological Society of America*, **100:1**, 384–391.

Sugita, H. and Tamura, K. (2008). Development of seismic design criteria for river facilities against large earthquakes. *Proceedings of the 14th World Conference on Earthquake Engineering.*