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A case study of soil liquefaction during the 2008 Wenchuan earthquake

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ABSTRACT: A field case study of liquefaction of sloping ground during the 2008 Wenchuan earthquake was conducted to reveal the liquefaction mechanism of shallow gravelly soil deposits. This case features its sand-gravel mixtures of high stiffness subjected to initial shear stress and extremely strong ground motion. The detailed information of ground motion, site description, subsurface soil conditions and field testing are presented. The liquefaction mechanism of gravelly soils could be attributed to the migration of sand portion from the sand-gravel mixture with the pore water pressure upward dissipation process, which was retarded at the interface between the gravelly soils and the overlying impermeable crust and caused the void redistribution and large lateral spreading.

1 INTRODUCTION

Liquefaction-induced lateral spreading and ground settlement in sloping ground have been well studied and most of them are about sand liquefaction (e.g., Fiegel & Kutter,1994; Valsamis et al.,2010; Kamai & Boulanger, 2013; Zhang et al., 2004; Khoshnevisan et al. 2015). However, liquefaction of gravelly soil deposits (i.e. gravelly sands and sandy gravels) discovered in the 2008 Wenchuan earthquake (e.g., Zhou et al., 2009) are rarely addressed, of which field manifestations, mechanism and evaluation seem quite different compared to those of typical sand liquefaction. Thus, high quality case studies of gravelly soils are of great interest.

This paper studies the liquefaction induced lateral spreading of gravelly soil deposits that occurred in the near-fault region at Yingxiu Town. This site features its alluvial fans along ancient courses, where the underlain liquefiable layers (i.e. the gravelly sands containing pebbles) are capped by non-liquefiable layers (i.e. an impermeable silty clay). This case study reveals several important mechanisms for explaining the susceptibility, triggering, and surface manifestations of liquefaction of gravelly soils with high shear modulus subjected to strong ground motions.

2 GROUND MOTION AND SITE DESCRIPTION

2.1 *Estimation of ground motion*

The peak ground motion of the investigated site was estimated from the USGS ShakeMap (see Figure 1) contributed by ATLAS in 2017. The white lines in Figure 1 are the PGA contours, and the mean and the corresponding variation of PGA are obtained by matching the site coordinates with the ShakeMap grids. The estimated PGA was 1.46 g with deviation 0.18g at this site.

2.2 *Site description*

The test site was on the Minjiang floodplain (free-field site), locating about 2 km southwest to Yingxiu town, Wenchuan county (103.477°E, 31.045°N, Elevation 854 m), with 12.7 km to the

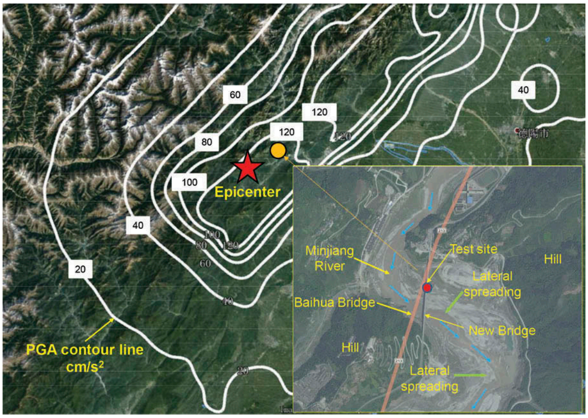

Figure 1. ShakeMap of the 2008 Wenchuan earthquake and the test site.

epicenter. The test site was on the left bank of the Minjiang River, which is an important tributary of the Yangtze River (see Figure 1). The Minjiang River zigzags successively near the test sites, which formulates the floodplain with land slopes ranging from 6.3% to 7.5%. The floodplain areas are covered with silty clay, gravelly soils and stiff rocks due to natural sedimentation.

2.3 *Field manifestation of liquefaction hazard*

Due to the extremely high ground motion acceleration and the long significant duration, which takes the time elapsed between 5% - 95% total integral of Arias intensity (Trifunac and Brady, 1975), large lateral spreading and ground settlements of the crust layer towards the Minjiang River were observed (see Figure 2(a) and (b)). Ground fissures could be found along the Minjiang floodplain with the observed cracks up to 40 cm, and some spots of boiled gravelly soils were identified as well (Li et al., 2008)(see Figure 2(a)). Along the stream bank, severe lateral spreading was found adjacent the bridge pier foundations and this might cause the supporting piers to tilt and contribute to the girder falling of the bridge, as shown in Figure 2(c) and (d).

2.4 *Subsurface soil conditions and field testing*

One borehole (see Figure 1) was conducted on the liquefied river bank to illustrate typical subsurface soil conditions as shown in Figures 3 and 4. In general, this site was underlain by fluvial deposits (geologic age,Q_4^{al+pl}) and boulders and weathered rocks (geologic age,T_{3X}) with shallow underground water (2.5 m below the surface). The thin silty clay crust of thickness 0.38 m underlain by gravelly sand (GC=40%) layer downward to 3.57 m. This gravelly sand layer contained some large-sized pebbles with GC=30% (i.e. particle size ranges from 10 mm to 100 mm, see Figure 3) and was underlain by medium to coarse sands with gravelly sands (GC=60%, downward to 4.31 m) and loose gravels (GC=70%, downward to 8.34 m). Below the depth of 8.34 m, boulders and weathered rocks were encountered. Stratification of the silty clay layer could be clearly discovered in Figure 3 as the soil particles at low parts were large while the upper parts were small, and low vertical permeability is expected at the interface of gravelly sand layer and the crust layer. Typical grain size distributions of the crust layer and the loose gravel layer were shown in Figure 4.

The shear wave velocities were obtained by spectral analysis of surface waves tests (SASW) on November 2008 (6 months after the event). By analyzing the phase information of the transfer function at each frequency, a set of dispersion data can be obtained and based on the dispersion curve, the variation in shear wave velocity with depth are then determined through a back-calculation process (Zhou et al., 2009; Yuan and Nazarian, 1993).The V_s and overburden stress corrected V_{s1} profiles and the critical layer were shown in Figure 5.

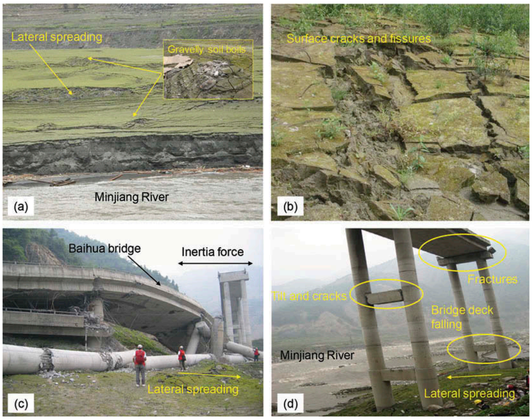

Figure 2. Liquefaction related damages: (a) lateral spreading and gravelly soil boils, (b) surface cracks and fissures, (c) collapse of the Baihua Bridge and (d) pier damage induced by lateral spreading

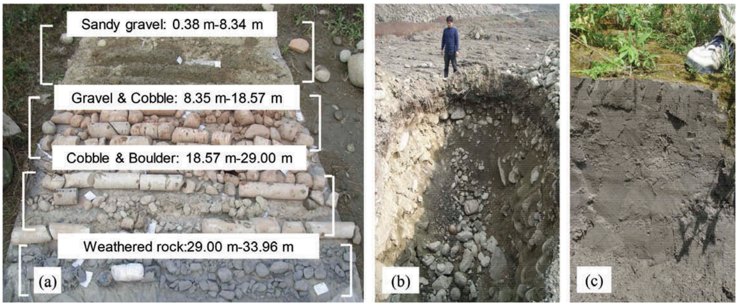

Figure 3. Field investigation: (a) boring records, (b) sand-gravel mixtures and (c) crust layer.

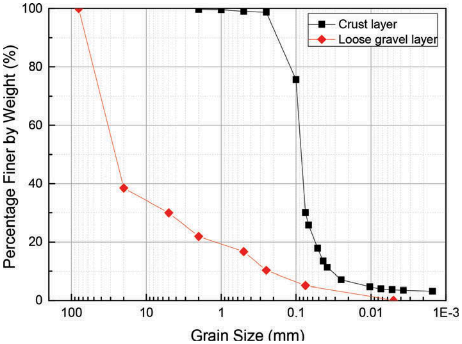

Figure 4. Typical grain size distributions.

3 POSSIBLE LIQUEFACTION MECHANISM

3.1 *Extreme strong ground motion*

The nearest strong motion station to the test site is Wolong Strong Motion Station (about 6 km to the test site) and the tri-directional acceleration time histories were shown in Figure 6 (a). The resultant tri-directional acceleration paths (see Figure 6(b)) implies a complex loading

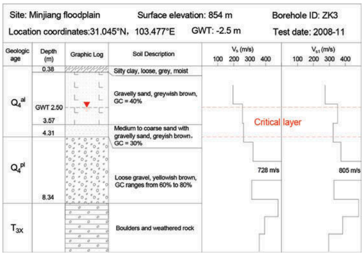

Figure 5. V_S profiles and critical layer at the site.

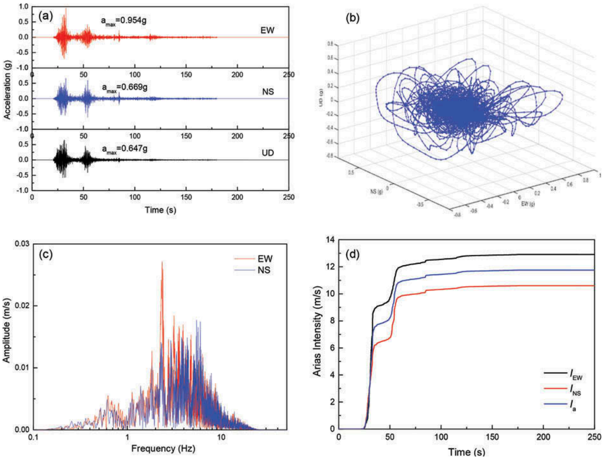

Figure 6. Record of Wolong Strong Motion Station: (a) tri-directional accelerations, (b) resultant acceleration paths, (c) FFT results and (d) Arias Intensity.

path in gravelly soils with cyclic shear and fast principal stress rotation. The Fast Fourier Transform (FFT) results show the dominant frequencies were about 2 Hz and 6 Hz in EW and NS direction respectively (see Figure 6(c)). As shown in Figure 6(d), the significant durations was about 52 s, and it could be found that the energy released in the near-fault region was faster and the consequent destructive effects on the ground were severer than other regions.

3.2 *High stiffness of gravelly soil deposits*

Traditionally, the gravelly soil deposits were recognized as non-liquefiable materials due to the high stiffness which can be verified from the V_S profiles, and were usually used in dam constructions. From the studies of Kokusho (2007), the gravelly soils could be liquefiable when they are loose enough. To evaluate liquefaction potential, a vital step is the selection of critical layer to find the stratum of soil that is the weakest-link-in-the-chain from a liquefaction perspective. In the case, the critical layer of the test site was identified as the layer of shallow loose gravelly sand and medium to coarse sand with gravelly sand, which could be solidly validated by the ejected gravelly soils as shown in Figure 3. The critical layer depth varied from 2.5 m to 4.31 m and the average overburden stress corrected shear wave velocity within it was 340 m/s. The depth range was also labeled in Figure 5.

According to Zhou et al. (2007) and Kayen et al. (2013), the deterministic shear-wave velocity-based assessment of liquefaction models indicate that when the normalized shear wave velocity reaches 300 m/s, it needs high CSR to trigger soil liquefaction (say, CSR higher than 1.0~1.5). While in this case the CSR was much lower than the critical CSR, which means these models need updating for gravelly soils.

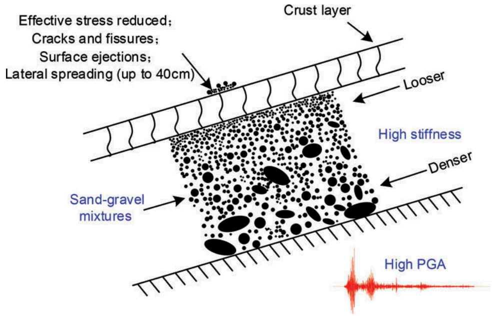

Figure 7. Liquefaction mechanism of sand-gravel mixtures (modified from Kamai & Boulanger, 2012).

3.3 *Sloping ground with impermeable crust*

It is well recognized that the initial static shear stress in sloping ground will contribute to the larger residual shear strain when subjected to cyclic shaking (Yang et al., 2011). However, the effect of combination of initial static stress and cyclic stress is still controversial (Youd et al., 2001), which is worth further studied for slopes of gravelly soils (i.e. sand-gravel mixtures).

Although the upper thin loose gravelly sand layer is prone to liquefy than the layer of medium to coarse sandy gravels in view of its high permeability (i.e. k = 28 m/d), the generation and upward dissipation of excess pore water pressure from the sandy gravel layers have significant effect for liquefaction triggering at the relatively shallow layer below the impermeable crust. As shown in Figure 7, excess pore water pressure will buildup during strong shaking. The accumulation of pore water pressure at the layer interface can lead to dilation and softening in the upper part of the liquefiable layer, which can in turn result in localized shear deformations. The smaller sand particles from the loosened sand-gravel mixtures will travel upward with the upward dissipation of pore water. Consequently, the upper parts of the liquefied layer will become looser due to soil dilation while the lower parts will be denser due to soil contraction. After the pore water pressure or the strain accumulated enough to form cracks in the crust layers, the sandy portions of sand-gravel mixtures will be ejected while most of the gravel portions remains stable underneath(e.g., Kokusho, 1999; Kamai & Boulanger, 2012). It can be expected that this process will not be as violent as void redistribution of sand due to the existence of large-sized gravel particle matrix. The ground failure caused by liquefaction of gravelly soils is not as severe as typical sand liquefaction, due to the fact that most of the gravels are still buried forming the soil skeleton with relative small strain. This particle migration and void redistribution process need to be further studied.

4 CONCLUSIONS

A case study of near-fault liquefaction during 2008 Wenchuan earthquake was carried out to reveal the liquefaction mechanism of gravelly soils. The detailed information of ground motion, site description, subsurface soil conditions and field testing are presented. Findings are as follows:

The liquefaction mechanism of sand-gravel mixtures could be attributed to the migration of sand portion from the sand-gravel mixture with the upward dissipation process, which was retarded at the interface between the gravelly soils and the overlying impermeable crust and caused the void redistribution and large lateral spreading. The initial shear stress in the sloping ground will increase the residual shear strain and help to form the surface fissures during strong shaking. These mechanisms need to be further studied.

This case features its sand-gravel mixtures of high stiffness subjected to initial shear stress and extreme strong ground motion, which is highly valuable for compiling liquefaction case histories for gravelly soils. Also the consequences of gravelly soil liquefaction are not as severe as typical sand liquefaction due to the fact that most large-sized gravel particles will remain stable underneath.

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REFERENCES

U. S. Geological Survey. M7.9-eastern Sichuan, China. Contributed by ATLAS 1, last updated 2017-04-1207:03:55 (UTC). https://earthquake.usgs.gov/earthquakes/eventpage/usp000g650#shakemap

Fiegel, G. L., & Kutter, B. L. (1994). Liquefaction-induced lateral spreading of mildly sloping ground. Journal of Geotechnical Engineering, 120(12),2236–2243.

Kamai, R., & Boulanger, R. W. (2012). Single-element simulations of partial-drainage effects under monotonic and cyclic loading. Soil Dynamics and Earthquake Engineering, 35, 29–40.

Kayen, R., Moss, R. E. S., Thompson, E. M., Seed, R. B., Cetin, K. O., Kiureghian, A. D., … & Tokimatsu, K. (2013). Shear-wave velocity–based probabilistic and deterministic assessment of seismic soil liquefaction potential. Journal of Geotechnical and Geoenvironmental Engineering, 139(3), 407–419.

Khoshnevisan, S., Juang, C. H., Zhou, Y. G., & Gong, W. P. (2015). Probabilistic assessment of liquefaction-induced lateral spreads using CPT—focusing on the 2010–2011 Canterbury earthquake sequence. Engineering Geology, 192, 113–128.

Kokusho, T. (1999). Water film in liquefied sand and its effect on lateral spread. Journal of Geotechnical and Geoenvironmental Engineering, 125(10), 817–826.

Kokusho, T. (2007). Liquefaction strengths of poorly-graded and well-graded granular soils investigated by lab tests. In Earthquake Geotechnical Engineering (pp. 159–184). Springer, Dordrecht.

Li, X., Zhou, Z., Yu, H., Wen, R., Lu, D., Huang, M., Zhou, Y.,& Cu, J. (2008). Strong motion observations and recordings from the great Wenchuan Earthquake. Earthquake Engineering and Engineering Vibration, 7(3), 235.

Trifunac, M.D., Brady, A.G., 1975. A study on the duration of strong earthquake ground motion. Bulletin of the Seismological Society of America, 65(3), 581–626.

Valsamis, A. I., Bouckovalas, G. D., & Papadimitriou, A. G. (2010). Parametric investigation of lateral spreading of gently sloping liquefied ground. Soil Dynamics and Earthquake Engineering, 30(6), 490–508.

Yang, J., & Sze, H. Y. (2011). Cyclic behaviour and resistance of saturated sand under non-symmetrical loading conditions. Géotechnique,61(1), 59–73.

Youd, T. L., & Idriss, I. M. (2001). Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. Journal of Geotechnical and Geoenvironmental Engineering, 127(4), 297–313.

Yuan, D.R., Nazarian, S., 1993. Automated surface wave method: inversion technique. Journal of Geotechnical Engineering. 119(7), 1112–1126.

Zhang, G., Robertson, P. K., & Brachman, R. W. I. (2004). Estimating liquefaction-induced lateral displacements using the standard penetration test or cone penetration test. Journal of Geotechnical and Geoenvironmental Engineering, 130(8), 861–871.

Zhou, Y. G., & Chen, Y. M. (2007). Laboratory investigation on assessing liquefaction resistance of sandy soils by shear wave velocity. Journal of Geotechnical and Geoenvironmental Engineering, 133 (8), 959–972.

Zhou, Y. G., Chen, Y.M., & Ling, D. S. (2009). Shear wave velocity-based liquefaction evaluation in the great Wenchuan earthquake: a preliminary case study. Earthquake Engineering and Engineering Vibration, 8(2), 231–239.