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# INVESTIGATION OF THE LIQUEFACTION POTENTIAL OF COAL ASH DUE TO SEISMIC LOADING

Ivan SLÁVIK[1*]

***Abstract***

*Coal ash is a geomaterial with a metastable structure. This type of geomaterial is significantly susceptible to liquefaction as a result of seismic loads. An investigation of ash that is susceptible to liquefaction due to a seismic load can use the CPT penetration test. This method of investigating liquefaction was developed based on numerous penetration tests of sandy or silty–sandy soils and was developed at the Workshop on the Evaluation of Soil Liquefaction Resistance, NCEER, Salk Lake City, Utah, USA, 1996. In the present article, the results of the CPT penetration test conducted at the Rosina ash tailings pond in Žilina in Slovakia, are analyzed using the NCEER methodology. The safety factor for ash liquefaction was expressed based on the penetration resistance values measured in the CPT tests using the 'LiquefyPro' software. The safety factor in the liquefaction of the ash sediment was expressed by changing the level of seeping water in the body of the tailings pond, the unit weight of coal ash, and the seismic acceleration.*

***Address***

[1] Department of Geotechnics, Slovak University of Technology, Faculty of Civil Engineering, Bratislava, Slovak Republic

* ***Corresponding author:*** ivan.slavik @stuba.sk

***Key words***

- Coal ash,
- Seismic load,
- Liquefaction,
- CPT cone penetration test,
- Safety factor.

## 1 INTRODUCTION

A method for investigating liquefaction caused by seismic activity was developed based on numerous penetration tests of sandy or silty–sandy soils and was developed in detail at the Workshop on Evaluation of Soil Liquefaction Resistance, NCEER, Salt Lake City, Utah, USA (Youd and Idriss, 1997). A standard penetration test (SPT) and cone penetration test (CPT) were used for investigating the liquefaction of sandy or silty–sandy soils caused by seismic activity.

The safety factor in liquefaction due to a seismic load $FS_{liq}$ can be determined based on Equation (1):

$$\mathrm{FS_{liq}} = \frac{\mathrm{CRR}}{\mathrm{CSR}} \tag{1}$$

If $FS_{liq} \geq 1.0$, soil liquefaction due to presumed seismic activity does not occur; on the other hand, if $FS_{liq} < 1.0$, the soil liquefies.

The *Cyclic Stress Ratio (CSR)* – seismic activity load can be expressed using Equation (2) defined in (Seed and Idriss, 1971).

$$\mathrm{CSR} = \left(\frac{\tau_{av}}{\sigma'_{vo}}\right) = 0.65.\left(\frac{a_{\max}}{g}\right).\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right).r_d \tag{2}$$

where $a_{max}$ is the maximum magnitude of the horizontal acceleration of the Earth´s surface caused by seismic activity; $g$ is the gravitational acceleration; $\sigma_{vo}$ is the total; $\sigma'_{vo}$ is the effective geostatic stress; and $r_d$ is the reduction coefficient, which depends on the depth below the surface of the surface as shown in Fig. 1.

The *Cyclic Resistance Ratio (CRR)* - The resistance of the soil to liquefaction can be determined based on the results of the cone penetration test (CPT). There are several methods to express *CRR* from the results of CPT testing using various methods (Seed and Idriss, 1971), (Robertson and Wride, 1997), (Suzuki et al., 1997). All the methods are based on an assessment of the high number of penetration tests at locations affected by seismic activity, where in some cases soil liquefaction has been observed in the ground, while in others, liquefaction has not occurred. In addition to the results of the penetration measurement, an additional verification of the seismic load intensity was also carried out at each location. These observations then resulted in the so-called *CRR* curve

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expressed in the *CSR* coordinate system (seismic activity load) – $q_{c1}$ (corrected magnitude of the penetration resistance), separating the measurements with liquefaction evidenced from the measurements without any liquefaction observed at the location. Examples of the *CRR* curves used in the respective methods are shown in Figs. 2a,b (see Fig. 2a (Robertson and Wride, 1997), see Fig. 2b (Suzuki et al., 1997)).

$$r_d = \frac{(\tau_{max})_d}{(\tau_{max})_r}$$

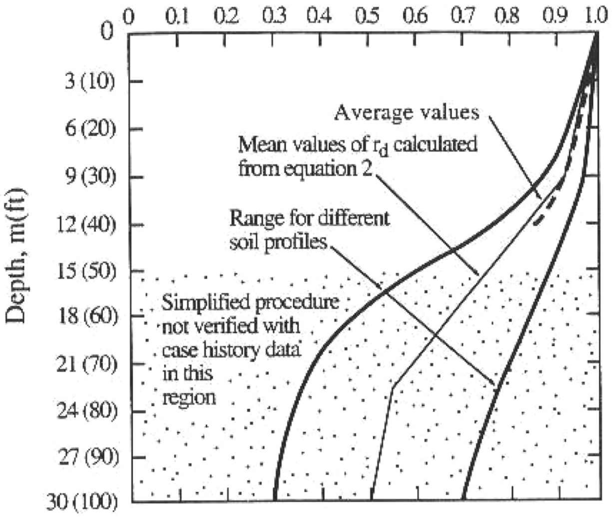



**Fig. 1** *Dependence of the reduction coefficient $r_d$ on the depth below the surface of the surface (Seed and Idriss, 1971)*

Correction of the measured penetration resistance $q_c$ is based on consideration of the magnitude of the effective geostatic stress or consideration of the content of fine grain particles in the soil. The *CRR* values were expressed for the magnitude of seismic activity, $M = 7.5$. Therefore, the $CRR_{7.5}$ notation is used. To accommodate these primary curves to magnitudes higher than or lower than 7.5, the correction factor *MSF* was established. In determining the degree of safety of liquefaction $FS_{liq}$, based on the $CRR_{7.5}$ values, this correction factor takes into account the required magnitude of seismic activity, which differs from 7.5. If the requested magnitude of seismic activity is greater or lower than 7.5, the degree of safety to liquefaction $FS_{liq}$ expressed by Equation 1 can be expressed based on the values of *CSR* and $CRR_{7.5}$ using Equation (3) as follows:

$$FS_{liq} = \frac{CRR_{7,5}.MSF}{CSR} \qquad (3)$$

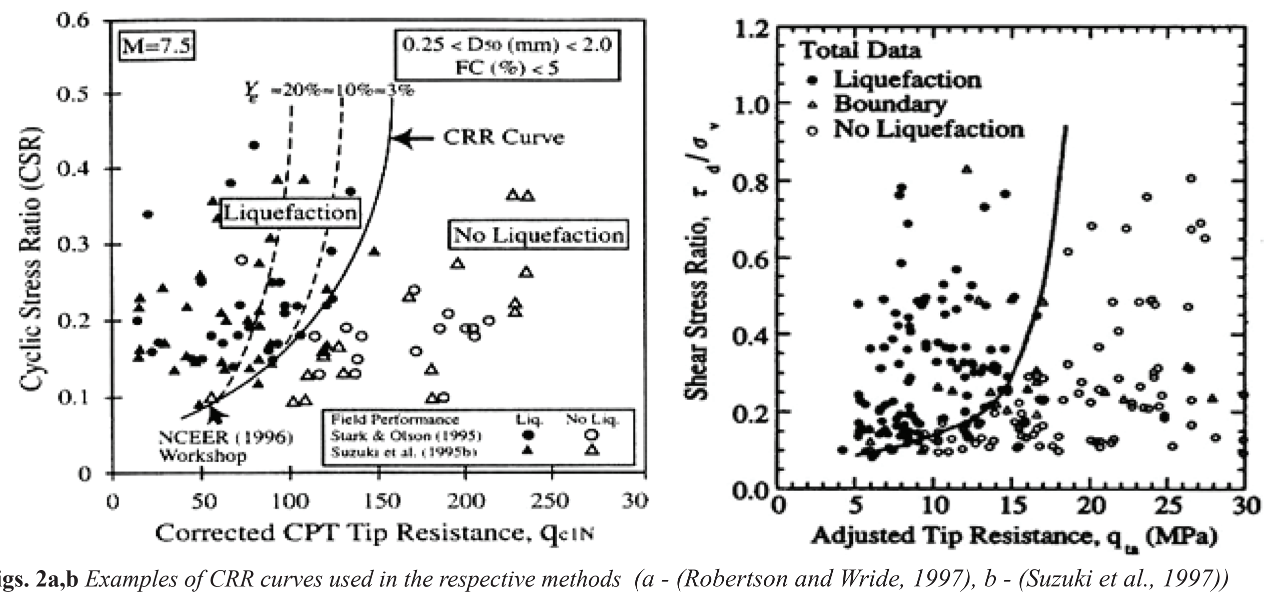
The magnitude of *MSF,* i.e., the factor which accounts for the scale of the magnitude of seismic activity can be expressed using Equation (4):

$$MSF = \frac{10^{2,24}}{M^{2,56}} \qquad (4)$$

## 2 MATERIALS AND METHODS

The coal ash is hydraulically transported through pipelines in the form of a slurry and floated on the beach of the tailings pond. The coal ash is deposited into the tailings pond by an ”against the water“ method. The dewatering of the ash deposition is ensured by the drainage system of the tailings pond. The main task of the drainage system is to maintain the lowest possible location of the phreatic surface in the tailings pond and in the dam bodies. The basic elements that make up the drainage system are the transverse drains of the tailings pond and the drainage of the starter dam.

Floated ash is a non-cohesive geomaterial with a typical low unit weight and high porosity. The unit weight values of the ash sediment in the tailings pond range from $\gamma_n = 11.0$ to $14.0\ kN.m^{-3}$, and the porosity of the ash is in the range n = 50 to 65 % (Slávik, 2012). This type of geomaterial is significantly susceptible to liquefaction as a result of a seismic load. An investigation of ash that is susceptible to liquefaction due to a seismic load can use certain field methods, which are currently most frequently employed to solve the same problem in sandy or sandy soils. We applied a method developed for the investigation of the liquefaction potential of sandy or silty–sandy soils due to their seismic load to a similar problem of brown coal ash located in the *Rosina* tailings pond located in the northwest of Slovakia on the outskirts of the city of Žilina (Masarovičová and Slávik, 2012). The granularity of the brown coal ash corresponds to the fine grain sand or the silty sand. The front view of the dam system of the *Rosina* tailings pond is in Fig. 3, and the side view is in Fig. 4.




**Figs. 2a,b** *Examples of CRR curves used in the respective methods (a - (Robertson and Wride, 1997), b - (Suzuki et al., 1997))*

**Fig. 3** *Front view of the dam system of the Rosina tailings pond*

**Fig. 4** *The side view of the dam system of the Rosina tailings pond*

Three static penetration tests, i.e., CPT – 1 to CPT – 3, were carried out at the location. The penetration tests were located parallel to the dam system of the tailings pond in the sedimentation area. The testing in the sedimentation area was facilitated by the interrupted operation of the tailings pond. The location and section of the tailings pond, together with the positions of the penetration tests, are shown in Figs. 5 and 6. The length of the penetration tests was approximately 20 m, which was implied by the requirement to inspect the total thickness of the ash sediment in the tailings pond.

Static penetration tests were carried out using a MAI-HAK-type assembly with a MDS 73-type point. The technical parameters of the static pentrometer were as follows: cone diameter = 35.7 mm; cone cross-section area - 10 cm$^2$; point angle - 60$^o$; diameter of the rod assembly = 32 mm; and progression rate – 25 cm.min$^{-1}$. During the static penetration test, the tip resistance $q_c$ [MPa], the sleeve friction $f_s$ [kPa], and the pore pressure $p_w$ [kPa] were measured.

According to the conclusions of the Workshop on Evaluation of Soil Liquefaction Resistance, NCEER, Salk Lake City, Utah, USA (Youd and Idriss, 1997), the US-based Civil Tech Corporation developed the 'LiquefyPro - Liquefaction and Settlement Analysis' program to investigate the susceptibility of a soil environment (loaded with seismic activity) to liquefaction using an evaluation of the results of a field penetration test. The safety factor for liquefaction was expressed based on the penetration resistance values measured in the CPT – 1 to CPT – 3 cone penetration tests using the 'LiquefyPro' software. The least favorable values of the penetration resistance were observed in the CPT – 2 penetration test. The results of the CPT – 2 static penetration tests were selected for presentation in this article. The safety factor for the liquefaction of the ash sediment of the tailings pond was expressed based on a parametric study. The parameters were the level of seeping water in the body of the tailings pond, the unit weight of the coal ash, and the seismic acceleration. The level of the seepage water was considered to be on a level with the surface

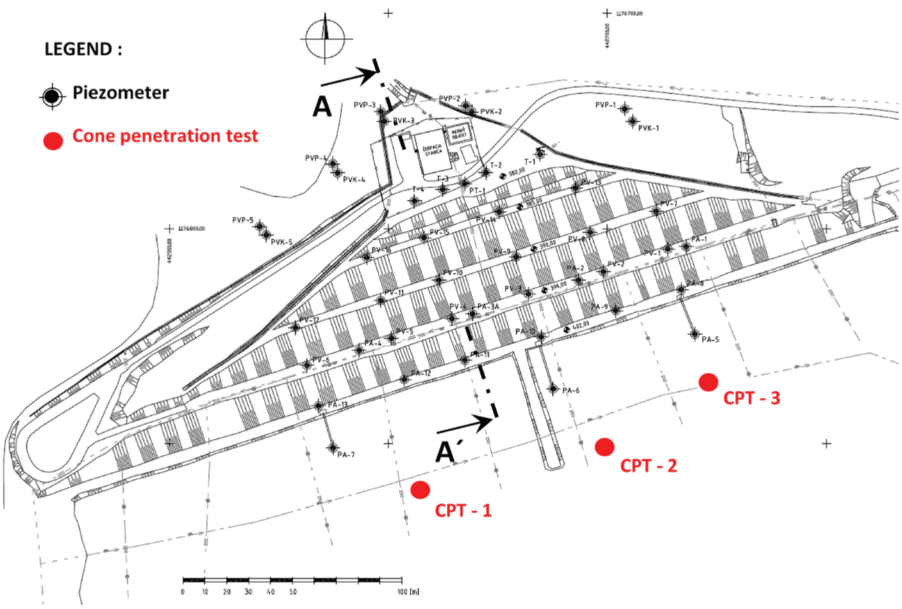



**Fig. 5** *Situation of the Rosina tailing pond in Žilina with the locations of the CPT tests*

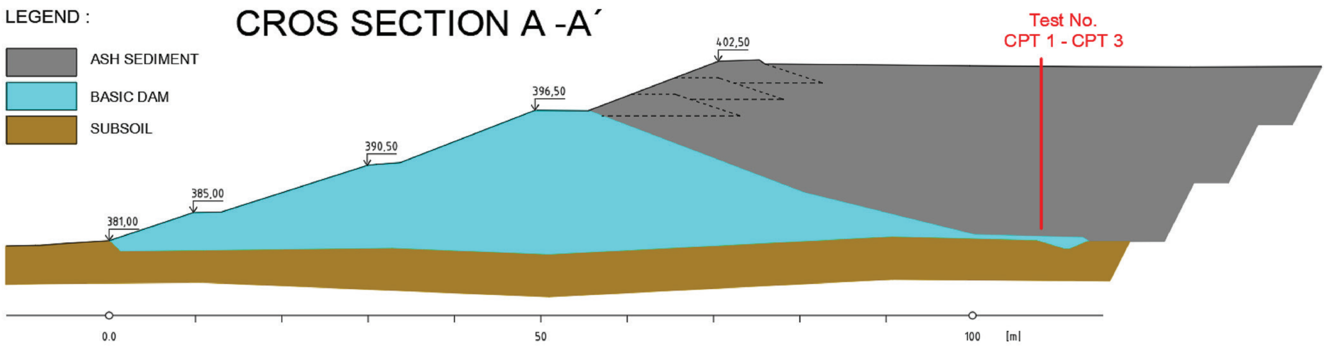



**Fig. 6** *Section of the Rosina tailing pond in Žilina with the locations of the CPT tests*

(in a tailings pond, this constitutes an accident) at the critical level as prescribed by the designer (it represents the most unfavorable real condition), at the limiting level as prescribed by the designer (represents the real condition), or without the water level. The unit weight in the natural deposition of brown-coal ash ranges from $\gamma_n$ = 11.0 to 14.0 kN.m$^{-3}$. The relative density of the ash was determined by the CPT – 1 to CPT – 3 in the range $I_D$ = 0.20 to 0.55. For the purpose of assessing the susceptibility of the ash sediment to liquefaction, the seismic load value of magnitude *M* and the peak ground acceleration (*PGA*) observations of the design seismic acceleration $a_g$ were considered. The magnitude *M* assigned to an earthquake with macroseismic effects was calculated using empirical equations with the epicentral intensities $I_0$. The epicentral intensities $I_0$ were determined in degrees of the MSK-64 macroscopic scale. For the territory of the Slovak Republic and the unknown depth of the hypocenter, the magnitude *M* can be determined using Equation (5):

$$M = 0.55\ I_0 + 0.95 \tag{5}$$

For the Žilina region (northwest Slovakia), where the tailings pond is located, the magnitude can be considered *M* = 0.55 x 8+0.95 = 5.35 ≈ 5.5; while the basic seismic acceleration for the area is $a_r$ = 1,0 m.s$^{-2}$, the design seismic acceleration was considered to be 1.25 times the basic acceleration $a_g = 1.25 x a_r = 1.25 x 1.0 = 1.25$. The acceleration was considered at PGA = $a_g$ / *g* = 1.25 / 9.81 ≈ 0.125.

## 3 RESULTS

The results of the analysis of the liquefaction of ash sediment in the tailings pond for the selected CPT – 2 penetration test are:

- ✓ Change in the level of water seepage in the body of the tailings pond at the average value of the unit weight of coal ash $\gamma_n$ = 12.5 kN.m$^{-3}$ considered, magnitude *M* = 5.5 and acceleration *PGA* = 0.125 in Figs. 7a, b, c, d (a – water level with surface; b – critical water level; c – limit water level; d – without any water level);
- ✓ Change in the level of the seeping water in the body of the tailings pond and change in the value of the unit weight of coal ash at the magnitude considered, i.e., *M* = 5.5, and acceleration *PGA* = 0.125 in Figs. 8a, b, c, d (a – water level with the surface and the unit weight of coal ash $\gamma_n$ = 11.0 kN.m$^{-3}$, b – water level with the surface and unit weight of coal ash $\gamma_n$ = 14.0 kN.m$^{-3}$; c – critical water level and unit weight of coal ash $\gamma_n$ = 11.0 kN.m$^{-3}$ and d – critical water level and unit weight of coal ash $\gamma_n$ = 14.0 kN.m$^{-3}$);
- ✓ Change in the maximum acceleration of the ground at the water level considered with the surface; the average value of the unit weight of coal ash $\gamma_n$ = 12.5 kN.m$^{-3}$ and magnitude *M* = 5.5 in Figs. 9a, b, c, d (a – maximum acceleration of the ground, PGA = 0.125; b – maximum acceleration of the ground, PGA = 0.100; c – maximum acceleration of the ground, PGA = 0.075; d – maximum acceleration of the ground PGA = 0.050).

The combinations of the boundary conditions for which the CPT results were assessed are presented in Tab. 1.

**Tab. 1** *The boundary conditions for which the CPT results were assessed*

| The level of water seepage in the body of the tailings pond | Unit weight of coal ash $\gamma_n$ [kN.m$^{-3}$] | | | Acceleration *PGA* [-] | | | |
|---|---|---|---|---|---|---|---|
| | 11.0 | 12.5 | 14.0 | 0.125 | 0.100 | 0.075 | 0.050 |
| Water level with the surface | *** +++ ooo | *** ooo | +++ | *** +++ ooo | ooo | ooo | ooo |
| Critical water level | *** +++ | *** | +++ | *** +++ | | | |
| Limit water level | *** | *** | | *** | | | |
| Without water level | *** | *** | | *** | | | |

*Note :* *** / +++ / ooo – *designation of the parameter selections in the combinations*

Each alternative describes the development of the *CSR* (seismic activity load) and *CRR* (resistance of ash sediment to liquefaction) values throughout the entire thickness of the ash sediment in the tailings pond. The sections where liquefaction occurred (*CSR* > *CRR*) are highlighted by hatching. In addition to the development of *CSR* and *CRR*, the safety factor for liquefaction $FS_{liq}$ is graphically expressed for the entire section. Such a graphic processing of the results of the penetration testing gives a clear view of places that could be affected by liquefaction due to the seismic activity considered.

In the case of the alternative of changing the water level in the body of the tailings pond (unit weight of ash, $\gamma_n$ = 12.5 kN.m$^{-3}$; acceleration, *PGA* = 0.125 Figs. 7a, b, c, d), the safety factor for liquefaction is $FS_{liq}$ < 1.0 if the water level exceeds the critical water level.

If the ash is characterized by the minimum value of the unit weight $\gamma_n$ = 11.0 kN.m$^{-3}$ (Figs. 8a, b, c, d), the safety factor for liquefaction is $FS_{liq}$ < 1.0 if the water level exceeds the critical water level.

In the case of the alternative of changing the acceleration (unit weight of ash $\gamma_n$ = 12.5 kN.m$^{-3}$, the water level considered with the surface Figs. 9a, b, c, d) the safety factor for liquefaction is $FS_{liq}$ < 1.0 if the acceleration level exceeds the value *PGA* = 0.05.

## 4 CONCLUSIONS

The evaluation of the safety factor for ash liquefaction using the above method shows that when characterizing the ash sediment deposited in the *Rosina* tailings pond in Žilina using its mean unit weight and maintaining the limiting water level in the body of the tailings pond, the ash sediment can be considered safe from the point of potential liquefaction due to the seismic load predicted for the given location (Fig. 7c). In the case of the predicted seismic load and critical water level in the tailings pond, part of the ash sediment in the tailings pond liquefies (Fig. 7b). After dewatering, the tailings pond will be safe from liquefaction during a seismic load (Fig. 7d). In the case of an accident (seepage water considered to be level with the surface), all the ash sediment in the tailings pond will liquefy (Fig. 7a). This case is unlikely.

The effect of the unit weight of the ash and the water level on the liquefaction of the ash sediment is presented in Fig. 8. In the case of the water level with the surface, the entire ash sediment would liquefy even when considering the minimum and maximum value of the unit weight of the ash (Figs. 8a, b). In the case of a critical water level, part of the ash sediment would liquefy when considering the minimum value of the unit weight of the ash (Fig. 8c), or the tailings pond will be safe from liquefaction when considering the maximum value of the unit weight of the ash (Fig. 8d).

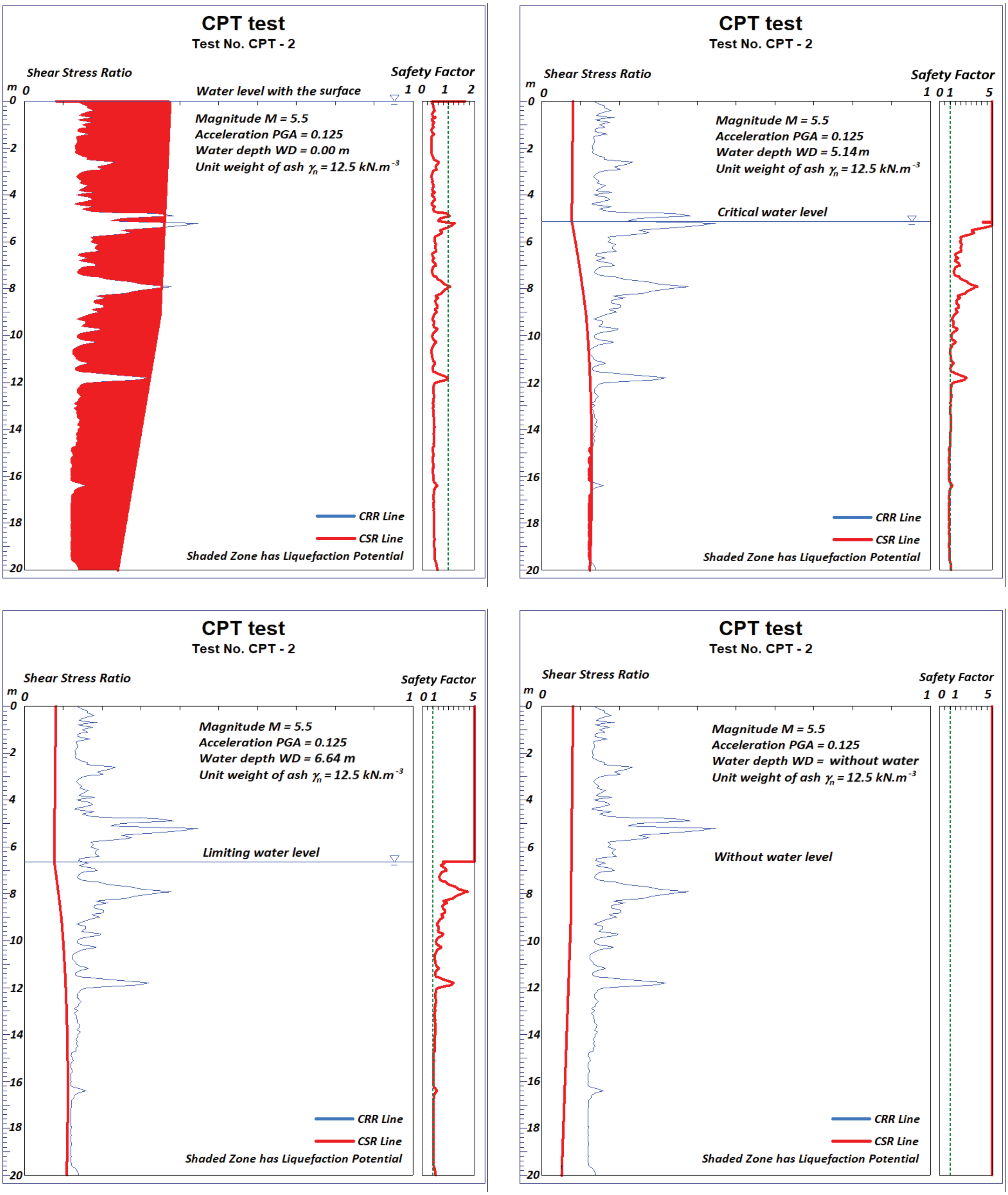
For the territory of the acceleration, i.e., the Slovak Republic, the values of the ground peak range from *PGA* = 0.05 to 0.125. The effect of the acceleration of the ground peak acceleration on the liquefaction of the ash sediment in the case of water level with the surface is presented in Fig. 9. At a ground peak acceleration ranging from *PGA* = 0.075 to 0.125, the entire ash sediment would liquefy (Figs. 9a, b, c). At the lowest ground peak acceleration considered, i.e., *PGA* = 0.050, only part of the ash sediment would liquefy (Fig. 9d).

The following general trends can be derived from the results of the liquefaction analysis of the ash sediment at the *Rosina* tailings pond located in the northwest of Slovakia on the outskirts of the city of Žilina, which was carried out using penetration tests:

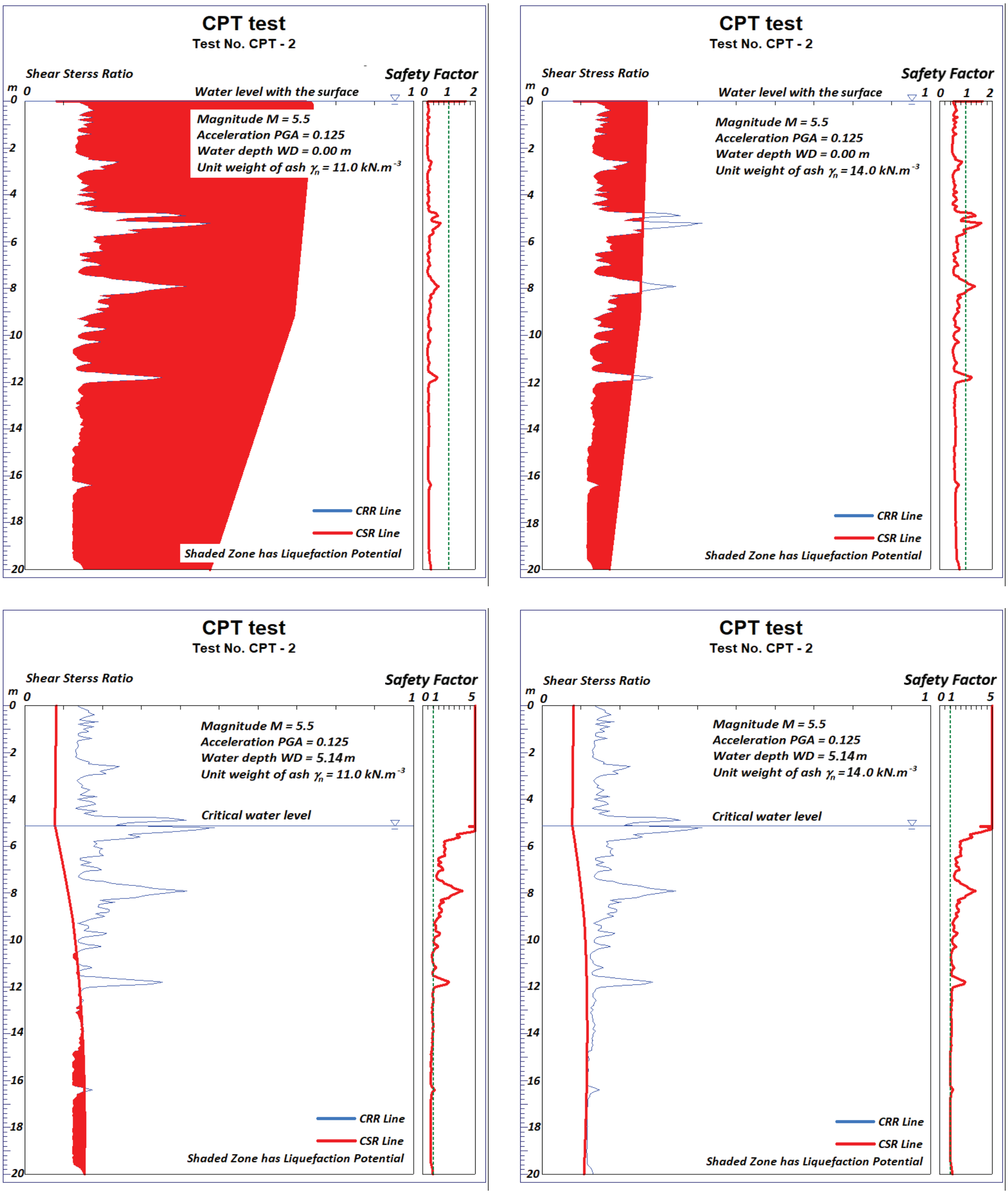
- ✓ increasing safety factor in liquefaction with a decreasing water level in the tailings pond;`
- ✓ increasing safety factor in liquefaction with increasing the unit weight of the ash;
- ✓ increasing safety factor in liquefaction with decreasing the peak ground acceleration.

Only three penetration tests, i.e., CPT – 1 to CPT – 3, were carried out at the tailings pond (see Fig. 5). From the point of view of the total volume of the tailings pond, these tests represent point measurements. Determining the volume of ash that could liquefy is very difficult. This would be possible if additional tests were added in a direction perpendicular to the direction of the CPT – 1 to CPT – 3 tests. Also, the evaluation of the differences and anomalies that could occur with respect to the general conclusions would be possible only by performing additional penetration tests.

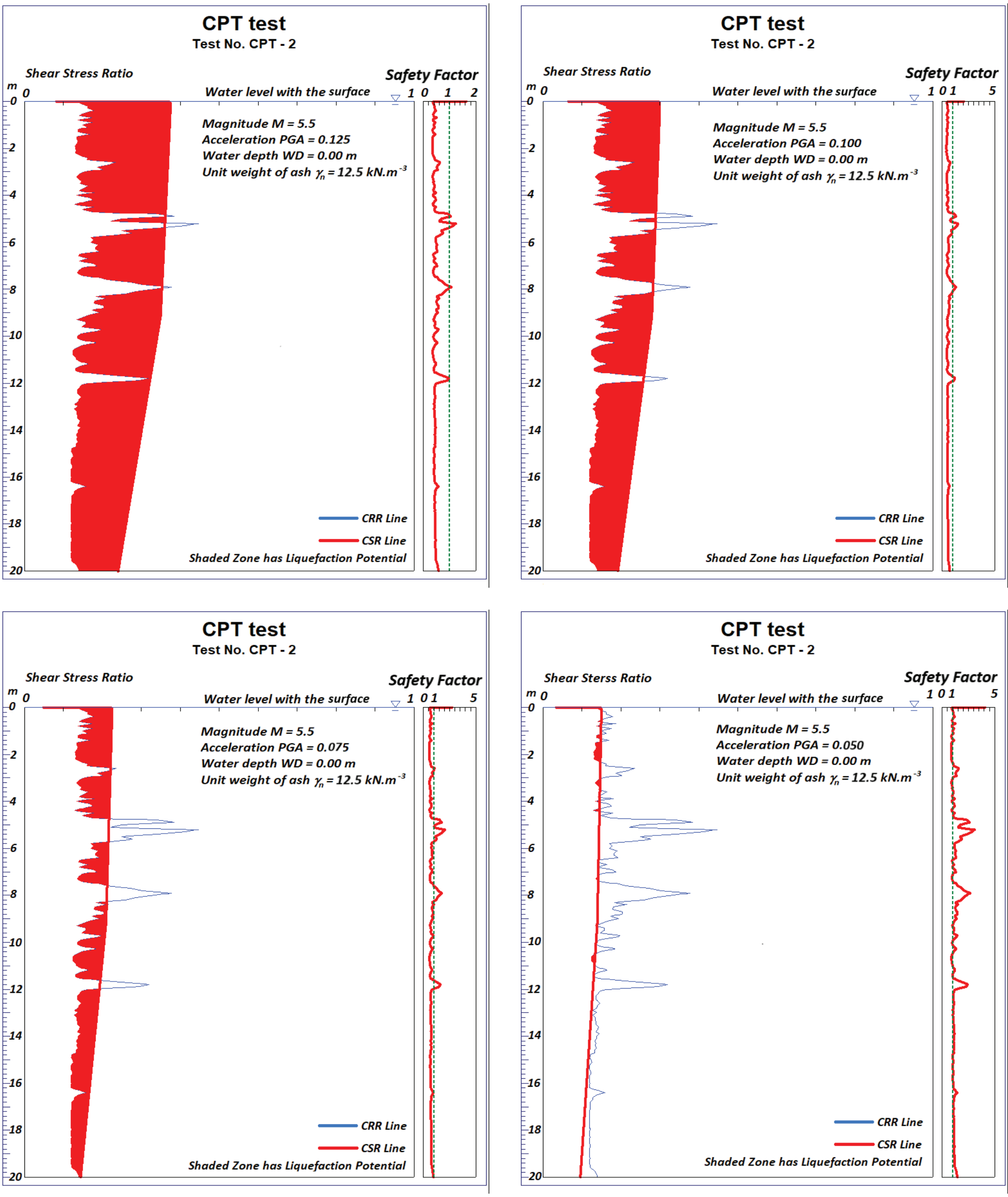
The methodology for evaluating the safety of ash sediment from liquefaction due to a seismic load could be useful in the evaluation of tailings ponds where the granularity composition of the sedimented materials is comparable to silty–sandy materials.




**Figs. 7a, b, c, d** *Results of the analysis of the ash sediment's liquefaction for the change in the level of seeping water in the body of the tailings pond (a - water level with surface; b - critical water level; c - limiting water level; d - without any water level)*




**Figs. 8a, b, c, d** *Results of the analysis of the ash sediment's liquefaction for the change in the level of seeping water in the body of the tailings pond and the change in the value of the unit weight of the coal ash (a - water level with the surface and unit weight of coal ash $\gamma_n$ = 11.0 kN.m$^{-3}$; b - water level with the surface and unit weight of coal ash $\gamma_n$ = 14.0 kN.m$^{-3}$; c - critical water level and unit weight of coal ash $\gamma_n$ = 11.0 kN.m$^{-3}$; d - critical water level and unit weight of coal ash $\gamma_n$ = 14.0 kN.m$^{-3}$)*




**Figs. 9a, b, c, d.** *Results of the analysis of the ash sediment's liquefaction for the change in the maximum ground acceleration (a - maximum ground acceleration PGA = 0.125; b - maximum ground acceleration PGA = 0.100; c - maximum ground acceleration PGA = 0.075; d - maximum ground acceleration PGA = 0.050)*

## REFERENCES

**Masarovičová, M., Slávik, I. (2012)** *Tailings Pond Žilina - Experimental research of the phenomenon of liquefaction of ash sediments*, STU Bratislava, Slovakia, p. 59, 2012 (in Slovak).

**Robertson, P.K., Wride, C.E. (1997)** *Cyclic liquefaction and its evaluation based on SPT and CPT*, Proc. Workshop on Evaluation of Liquefaction Resistance of Soils, 1997, ISSN 1088-3800, pp. 41-88.

**Seed, H.B., Idriss, I.M. (1971)** *Simplified procedure for evaluating soil liquefaction potential*, Journal of the Division of Soil Mechanical and Foundations, ASCE, Vol.107, No. SM9, 1971, 1249-1274.

**Slávik, I. (2012)** *Monitoring the geotechnical properties of geomaterials of impoundments*, Habilitation thesis, STU Bratislava, Slovakia, p. 173, 2012 (in Slovak).

**Suzuki, Y., Koyamada, K., Tokimatsu, K. (1997)** *Prediction of liquefaction resistance based on CPT tip resistance and sleeve friction*, Proc. of XIV International Conference on Soil Mechanics and Foundation Engineering, Hamburg, Germany, 1997, ISBN 9789054108955, pp. 603-606.

**Youd, T.L., Idriss, I.M. (1997)** *Technical Report NCEER-97-0022*, Proc. of the NEECR Workshop on Evaluation of Liquefaction Resistance of Soils, 1997, 276 pp. 276.