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Comparison of liquefaction evaluation based on SPT and geophysical tests (case study: Mahabad dam, Iran)

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ABSTRACT: Standard Penetration Test (SPT) is the most commonly used insitu test for soil characterization, including the liquefaction resistance. Many studies have sought to correlate SPT number to cyclic resistance ratio (CRR) as a frequently-used approach for assessment of liquefaction potential. However, it has been shown that SPT has major deficiencies (e.g., inaccuracy in coarse sands and clays) which have given rise to development and utilization of new characterization methods such as geophysical tests (e.g., down-hole and cross-hole). In this paper, a comparison is made between the results of SPT and geophysical tests in three boreholes through the body and foundation of Mahabad Dam (located in north-western part of Iran) and the corresponding assessment of liquefaction potential. It is shown that the cyclic resistance stresses obtained by SPT are lower than those obtained by geophysical tests. Hence, some parts of the dam body are found close to being liquefiable by means of SPT tests, whereas geophysical tests prove the dam site to be safer, indicating considerable discrepancy between the two methods. Additionally, for some parts of the dam body and especially dam foundation where confining pressures are high or the soil is very dense and SPT number (N) is not an applicable characterization measure, shear wave velocities obtained by geophysical tests provide a meaningful tool for assessment of liquefaction potential.

1 INTRODUCTION

The liquefaction potential in soils can simply be evaluated by means of semi-empirical methods by using conventional geotechnical and geophysical site characterization tests. The simplified procedure originally proposed by Seed and Idriss (1971) has been used as the main framework and takes advantage of cyclic resistance ratio (CRR) curves. Initially, this method was based on results obtained by Standard Penetration Test (SPT), however, other geotechnical and geophysical site characterization tests (e.g., cone penetration tests (CPT) and geophysical tests for small-strain shear wave velocity measurement) began to be used as alternatives.

Despite the fact that a larger database is available on real case histories to develop liquefaction potential correlations using SPT or CPT methods, some significant disadvantages make these penetration-type tests not applicable in all conditions. At large depths, such as those encountered under large embankment dams, penetration-type tests are sometimes not feasible and in addition, the available SPT and CPT data are limited to σ'_v/P_a less than about 5.5 and 7, respectively (Boulanger 2003). Penetration-type soil characterization tests are not convenient as well to be performed in some soil types, such as those with large particle size (e.g. gravels and boulders). Consequently, more attention has been drawn to shear wave velocity (V_s) of soils as a useful measure in liquefaction resistance evaluation. According to previous studies, it has been shown that a good precision exists between V_s and the resistance to liquefaction (De Alba et al. 1984; Tokimatsu et al. 1986; Tokimatsu and Uchida 1990). Although respective sensitivity to relative density, D_R, is lower in V_s compared to SPT and CPT test results (Idriss and Boulanger 2006), the fact that verifies the feasibility of V_s for liquefaction evaluation is that some important soil characteristics such as soil fabric and strains caused by past earthquakes, influence the liquefaction resistance and shear wave velocity in a comparable way (Yunmin et al. 2005).

In the present paper, results of SPT and geophysical tests (down-hole and cross-hole) conducted through the body and foundation of Mahabad Dam are presented and the liquefaction potential of the dam body and foundation is evaluated using both test types. The general guidelines provided by Yunmin et al. (2005) are implemented to assess the CRR curves by means of V_S. Lastly, a discussion is made about the obtained liquefaction evaluation curves by SPT and V_s approaches.

2 LOCATION AND GEOLOGICAL SITE CONDITIONS

2.1 *General site conditions*

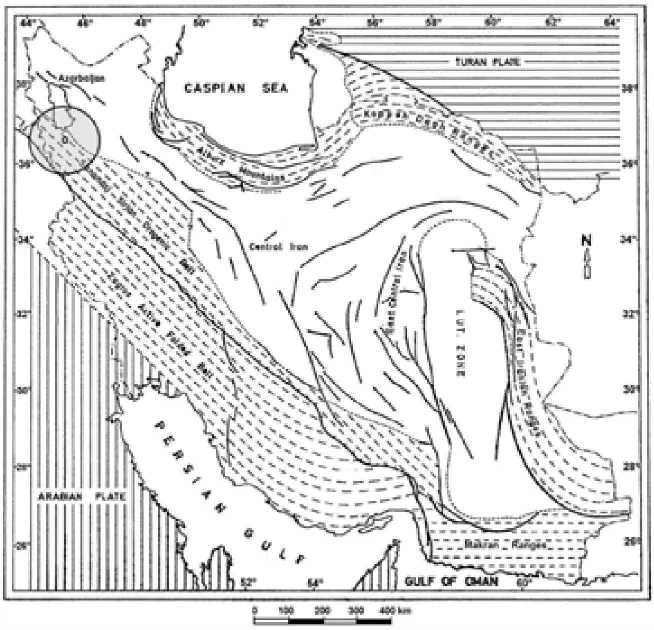
Mahabad Dam is an embankment dam located about 1 km west of the City of Mahabad, in the Western Azerbaijan Province of Iran. Construction of the dam was completed in 1970; the capacity of the dam reservoir, at the normal water level (1359.1 m.a.s.l.), is about 230 million cubic meters. The dam is located on the Sanandaj-Sirjan Belt (Figure 1-a) and on an alluvial foundation of silty sand with fine-grained and coarse-grained sandy lenses. The South Mahabad Fault is situated about 3.5 km on the south of Mahabad dam and is considered as the most effective fault on the dam site (Figure 1-b). Thickness of the alluvial strata is approximately 25 meters under the right abutment and near 8 meters under the left abutment. The high reservoir capacity of the dam, being located near a large city together with being susceptible to seismic activities and a potential liquefiable foundation, necessitate a thorough liquefaction analysis for this 45-year-old embankment dam.

2.2 *Determination of the peak ground acceleration (PGA)*

For determination of the strong ground motion parameters at Mahabad Dam site, especially the peak ground acceleration (PGA) used for semi-empirical liquefaction potential assessment, different methods of deterministic and probabilistic seismic hazard analyses were applied. The probabilistic line-source method proposed by Cornell (1968) were used for evaluation of various seismic levels, including CE (Construction Earthquake), ODE (Operating Basis Earthquake), DBE (Design Basis Earthquake) and MDE (Maximum Design Earthquake) by means of the software SEISRISK-III (Bender and Perkins 1987). To obtain the Maximum Credible Earthquake (MCE), a number of attenuation relationships (Ambraseys et al 2005, Campbell and Bozorgnia 2008, Akkar and Bommer 2010), with considering different faults as the seismic source, were examined by a deterministic approach. Results indicate that the largest earthquake by the South Mahabad Fault is *Ms=6.4*, causing a maximum horizontal acceleration of about *PHA=0.50g* at the dam site (Table 1).

Table 1. Values of maximum strong motion accelerations at the Mahabad dam site for different design earthquakes

Criteria	Return period (years)	Analysis method	Max. horizontal acceleration (g)
CE	80% of OBE	Probabilistic	0.08
OBE	145	Probabilistic	0.10
DBE	475	Probabilistic	0.16
MDE	2000	Probabilistic	0.27
MCE	Deterministic		0.50



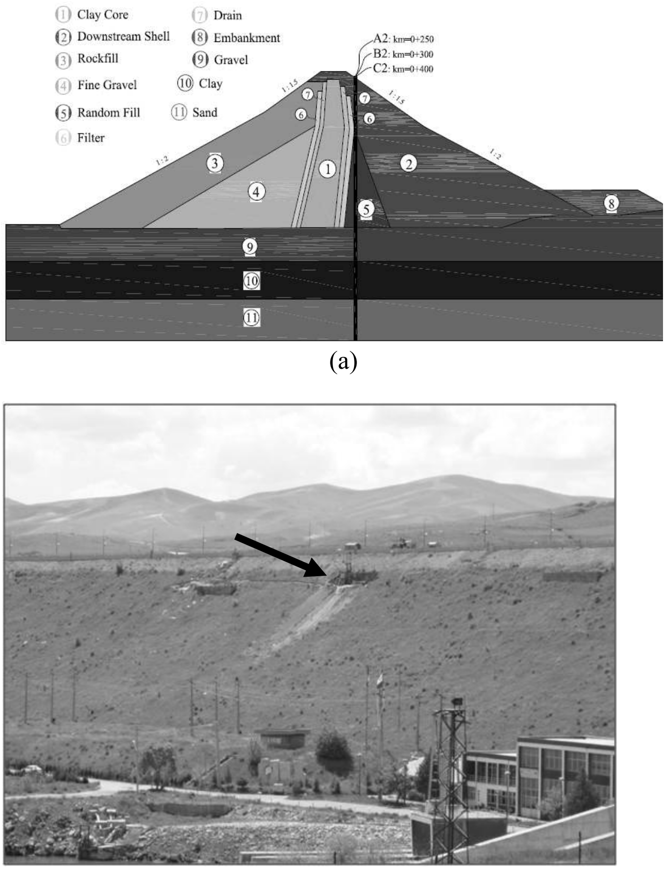
(a)

(b)

Figure 1. Mahabad Dam site; (a) location of the dam inside the Sanandaj-Sirjan Belt (b), the nearest faults (looking to west)

3 FIELD INVESTIGATIONS

Standard penetration tests (SPT) and small-strain geophysical tests (down-hole and cross-hole) were performed through the Mahabad dam body and foundation in 2013 and 2015, respectively. Three primary boreholes were drilled, topping from approximately 7 meters below the dam crest at three different sections for the purpose of carrying out the standard penetration tests (A2 at km=0+250, B2 at km=0+300, C2 at km=0+400, all distances measured from the end of the crest on the left abutment). As seen in Figure 2, A2, B2 and C2 boreholes were drilled through the downstream shell into the dam foundation at depths of 90, 85 and 85 meters, respectively. Secondary boreholes were also drilled next to each primary borehole for the purpose of cross-hole seismic tests.



(a)

(b)

Figure 2. (a) Main section and borehole positions at Mahabad Dam (b) A view from downstream slope of the dam and placement of the drilling equipment near the crest

3.1 *Standard penetration tests (SPT)*

The liquefaction resistance evaluation of the dam body and foundation may be directly assessed by means of the SPT *N*-value (Seed and Idriss, 1971). Alternatively, correlations can be used to convert SPT *N*-values to the corresponding shear wave velocities (V_S) which are then used to evaluate the liquefaction resistance of soils. In this study, the latter approach was implemented making it possible to directly compare the results of geotechnical and geophysical tests. A total number of 121 standard penetration tests were performed inside the three boreholes at the dam. For the purpose of obtaining V_s from the SPT *N*-value, 8 correlations were used (Shibata, 1970; Ohta et al, 1972; Imai & Tonouchi, 1982; Sykora & Stokoe, 1983; Okamoto et al, 1989; Lee, 1990; Hasancebi & Ulusay, 2006; Dikemen, 2009). The average V_s (not V_{s1}) achieved by these correlations are plotted in Figure 3.

3.2 *Geophysical tests (down-hole and cross-hole)*

In the second-phase of filed investigations, geophysical tests were carried out in the form of down-hole and cross-hole tests. A secondary borehole was drilled adjacent to each primary borehole for the purpose of cross-hole tests. Geophones were placed inside the primary boreholes at every two meters and a shear wave source was placed at the top of the boreholes for down-hole tests, while in cross-hole tests, shear waves were produced in the secondary boreholes at 2-meter intervals and recorded at the primary boreholes. The shear wave velocities were calculated for the three boreholes and the results are shown in Figure 3. As observed in this figure, shear wave velocities obtained by both geophysical methods are quite the same. However, results show that at depths greater than 20 meters, the standard penetration tests, underestimate the shear wave velocities and this, in particular, is a result of inaccuracy of *N*-V_s correlations for high confining pressures at medium depths (20-50 m). Additionally, it is observed that at greater depths (e.g., >50 m), SPT tests were refused (N>50). As a result, the obtained V_S values based on SPT results are not useful. As previously mentioned, this is a clear example of shortcomings of penetration-type tests such as SPT at large depths.

4 LIQUEFACTION POTENTIAL ASSESSMENT

The criterion proposed by Yunmin et al. (2005) was used to estimate the liquefaction potential at the three boreholes through the body and foundation of Mahabad Dam. This method takes advantage of comparing the earthquake-induced cyclic shear stress ratio, CSR, with the cyclic resistance ratio, CRR, as a function of stress-corrected shear wave velocity (V_{s1}). The liquefaction potential based on SPT and geophysical tests is assessed and depicted in Figure 4. The figure shows that SPT results evaluate the liquefaction potential inside the non-liquefiable zone but very close to the potentially liquefiable zone. Nevertheless, the results obtained by geophysical tests demonstrate a greater liquefaction safety factor in comparison with SPT results. As discussed before, this may be attributed to the limitations of penetration-type field investigations for liquefaction evaluation at large depths (e.g., greater than 20 meters).

5 CONCLUSIONS

Mahabad Dam was constructed more than 45 years ago in the Western Azerbaijan Province, Iran. At the time it was built, the knowledge about soil liquefaction was very limited. Therefore, no reasonable investigations were carried out to evaluate the liquefaction potential of the dam body and foundation. Recently, a set of complementary geotechnical (SPT) and geophysical (down-hole and cross-hole) site investigations were conducted to characterize soil conditions and obtain the shear wave velocities at the dam site. The data were then used to assess the

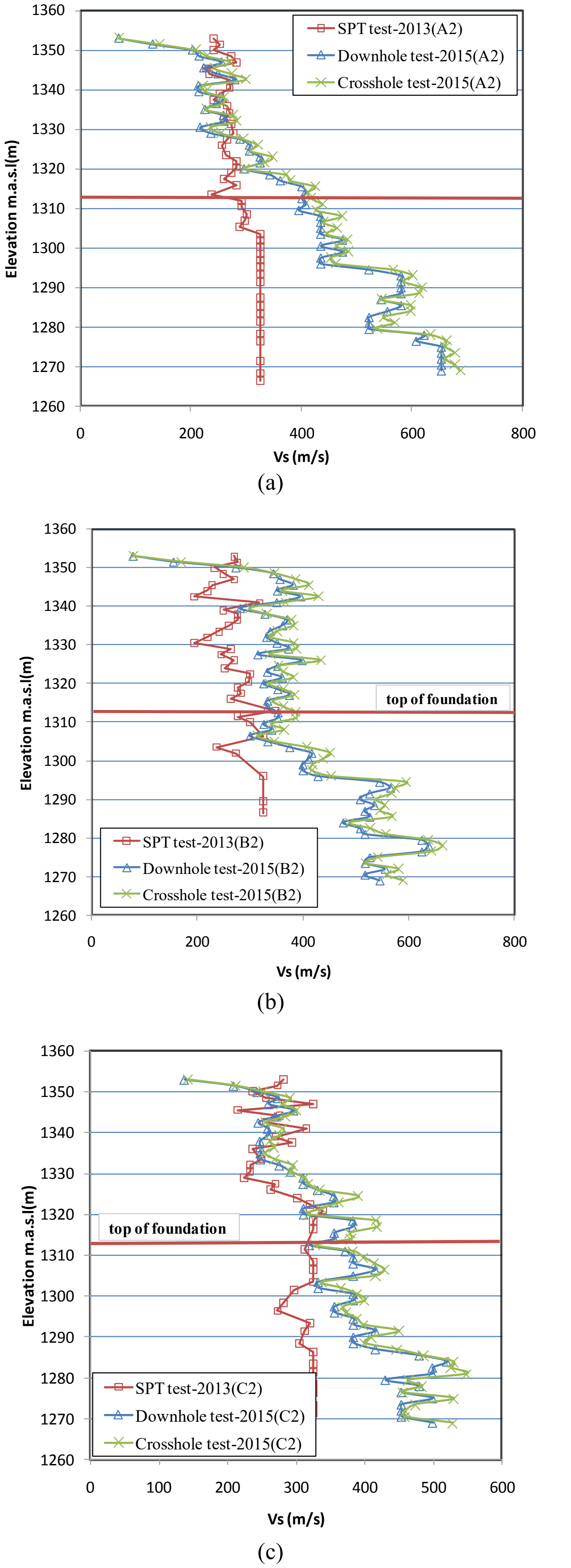


Figure 3. Shear wave velocity profiles for (a) A2, (b) B2, and (c) C2 boreholes obtained by SPT, down-hole and cross-hole tests

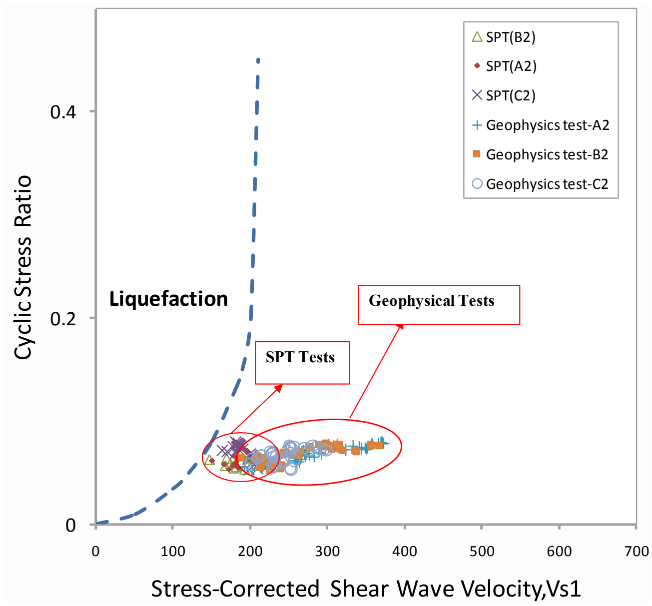


Figure 4. Liquefaction potential assessment at Mahabad Dam body and foundation, cyclic shear stress ratio (CSR) vs. stress-corrected shear wave velocity (V_{s1})

liquefaction potential of the dam body and foundation. Results indicate that the correlations used for converting the SPT *N*-Value to V_s are accurate only at small depths and should be used with caution for medium to large depths (>20 m). Although a larger database is available for liquefaction potential correlations developed by means of SPT, penetration-type tests are not feasible at large depths (> 50 m), typically encountered in large embankments such as earth dams. The geophysical values for the stress-corrected shear wave velocities (V_{s1}), as an indication of the cyclic resistance ratio (CRR), are significantly higher on average than those obtained by the SPT, and in this case seem to be more reliable, demonstrating no liquefaction exposure for the Mahabad Dam.

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