LIQUEFACTION ASSESSMENT OF INDUS SANDS USING SHEAR WAVE VELOCITY

Sohail Kibria[1], M. Javed[2], Muhammad Ali[3]

ABSTRACT

A host of procedures are available for identification and quantification of liquefaction potential of submerged sand deposits present in a seismic environment.

A general database exists in the literature to approximately identify the liquefaction potential of sands on the basis of shear wave velocity. Such correlations are not considered adequate for quantification of the liquefaction potential which is a function of a number of variables, like grain size characteristics, extent of grain packing, the geologic nature/age of the deposit, the level of seismicity, the position of groundwater table etc.

An elaborate study followed by rigorous analyses has been carried out by the authors to establish a correlation between the liquefaction potential of Indus sands and shear wave velocity at Chashma, on the basis of evaluated using state-of-the-art methods in a free-field condition under peak ground acceleration (PGA) of 0.1 g, 0.2 g, and 0.3 g. The data of standard penetration test (SPTs) and cross-hole measurements has been utilized in this research.

The resulting correlations between the shear wave velocity and the factor of safety against liquefaction are presented in this paper to assess the threshold shear wave velocity indicating the triggering of ground liquefaction.

It is believed that the findings of this paper will be of immense benefit to the geotechnical and structural engineering community for quick estimation of the liquefaction potential of the Indus sands (or similar sands)on the basis of shear wave velocity.

INTRODUCTION

The phenomenon of build-up of high pore water pressure under pulsating load, in the sands below groundwater table has been widely reported in the geotechnical literature to trigger cyclic mobility or leading to full-fledged ground liquefaction. Besides earthquake loading, the blast-induced seismicity and machinery vibration can cause significant increase in pore-pressure thereby reducing/eliminating effective stresses in the soils, momentarily.

In view of the seriousness of the liquefaction after-effects, its evaluation has been attempted by a host of methods/techniques by various researchers. These include use of standard penetration tests (SPT) and cone penetration tests (CPT) as the main field tests besides the cyclic triaxial liquefaction tests in the laboratory.

In addition to the above, range of shear wave velocity in a submerged sand deposit has also been reported to develop a qualitative feel for the liquefaction potential, alongwith the associated earthquake magnitude. Such qualitative feelers have been developed by Seed et.al. (Ref. 1).

1. Head Foundation & Pavement Section, GT & GE Division, NESPAK, Lahore
2. Principal Geophysicist, GT & GE Division, NESPAK, Lahore
3. Geotechnical Engineering, GT & GE Division, NESPAK, Lahore

This paper depicts an interesting comparison of the liquefaction potential evaluated by the state-of-the-art free-field SPT method (as per Seed and Harder) and the measured shear wave velocities for a safety factor of unity against liquefaction. The extensive database of Chashma Hydropower Project site (Ref. 2 & 3) has been used in this study. Finally threshold shear wave velocities of the Indus sand at Chashma have been determined to trigger liquefaction for various horizontal ground accelerations 0.1g to 0.3g.

Geotechnical Characterization of Indus Sands

The geotechnical characteristics of the Indus sand deposits at Chashma were determined in detail during the design/construction stage studies for Chashma Hydropower Project. These studies essentially included, besides others, execution of 3 boreholes upto 41 to 100 m depth (SPT-1 to SPT-3) along with SPT measurements at 1.0 to 1.5 m depth interval, performance of cone penetration tests (CPTs) at 3 locations upto 26 to 28 m depth (CPT-1 to CPT-3) and performance of a series of static and dynamic tests in the laboratory, at the powerhouse site. (Ref. 2 & 3).

The variation of SPT and CPT measurement over the depth of bores are shown in Fig. 1 to 3. The grain size distribution of these sands is shown in Fig. 4, in relation with other known liquefiable sands. In general, the sand deposits consist of medium-dense to dense fine sands in the upper 25 to 35 m deep zone, followed by dense to very dense fine sands. These sands have traces of silt content. The groundwater table was found almost at the ground surface. The drained angle of shearing resistance of these sands in the upper zone varies from 30° to 34° while for the lower deposits it ranges between 34° and 38°.

State-of-the-art for Liquefaction Assessment.

The free-field liquefaction analysis of ground is today regarded as the state-of-the-art for evaluation of liquefaction potential. Rollins and Seed have elaborated this point as "The current state-of-the-art practice in analyzing the potential of liquefaction beneath a structure is to treat the soil as if it were in the free-field under level ground conditions and ignore any effect of the building" (Ref. 4). In consonance with the above ruling, free-field liquefaction analysis of the SPT data was carried out, as per guidelines provided by Seed and Harder (Ref. 5).

Free-Field Liquefaction Potential Using SPT

The analysis was carried out on the most sophisticated concepts in the liquefaction studies. The following main steps were involved in the systematic evaluation of the liquefaction potential:

a) Energy measurement during SPT with a load cell and a digital calibrator unit.

b) Correction of recorded SPT for energy, overburden and other factors, as proposed by Skempton (1986, Geotechnique).

c) Evaluation of correction factors for earthquake magnitude (M = 6.5), confining pressure and pre-existing shear stress, as per Seed and Harder.

d) Evaluation of cyclic stress ratio required to cause liquefaction (CSR_l).

e) Evaluation of cyclic stress ratio induced by earthquake (CSR_{eq}) for peak ground accelerations (PGA) of 0.10 g, 0.20 g and 0.30 g.

f) Evaluation of safety factor against liquefaction at various depths for PGA of 0.10 g, 0.20 g and 0.30 g using the expression "CSR_l/CSR_{eq}".

Fig. 5 shows variation of computed safety factors with depth.

Shear Wave Velocity Measurement

Cross-hole survey has been carried out at two locations, upto 40 to 95 m depth in the boreholes, using a 12 channel signal enhancement seismograph. For each test setup, a system of one impact hole and two listening holes (L_1-L_2 and L_3-L_4) was used. Properly cased and grouted boreholes of 150 mm diameter were executed for this purpose. In order to know the correct travel distances and hence the correct velocities, inclinometer survey was also carried out in the boreholes. The measurements were recorded at 1.0 m interval in the boreholes, (Ref. 6).

The shear wave velocities were calculated by dividing the distance between receivers, by the travelling time from one receiver to the other. The measured shear wave velocities are found to vary with depth, as shown in Fig. 6.

Liquefaction Potential – Shear Wave Velocity Correlation

The factors of safety available against liquefaction of Indus sands at Chashma at various depths below top of ground for the three PGA levels of 0.10 g to 0.30 g are shown plotted in Fig. 5.

The safety of a structure to be constructed on such deposits demands that a design control be established with regard to the lower limits of safety factors available over the area. Accordingly, lower limits of factor of safety have been deduced and plotted with depth as shown on Fig. 7. The variation of shear wave velocity with depth is also shown on Fig. 7 in the form of data envelope. For safety factor of 1.0 against liquefaction, the following threshold shear wave velocities (Table 1) have been determined for PGA of 0.1 g, 0.2 g and 0.3 g from this figure:

Table 1

Range of Threshold Shear Wave Velocity and the estimated zone of liquefaction

PGA	Range of Threshold Shear Wave Velocity (m/sec.)	Estimated Zone of Liquefaction (m)
0.10 g	200 – 230	0.0 – 16.0
0.20 g	235 – 265	0.0 – 25.0
0.30 g	275 – 310	0.0 - 35.0

These analyses suggest that there is a distinct threshold shear wave velocity of Indus sands for triggering liquefaction of the ground, for various horizontal ground accelerations (PGA).

The upper limit of threshold shear wave velocities (for which free-field factor of safety of 1.0 is available against liquefaction) is shown in Fig. 8. The figure shows that the shear wave velocity is not an independent variable for assessment of liquefaction potential of submerged sands; it must be considered along with the design PGA, for evaluation of the liquefaction potential of submerged sands, similar in character to Indus sands. The threshold shear wave velocity for Indus sand deposit at chashma, to be safe against liquefaction, has been evaluated by a regression analysis of the data as under:

$$Vs = 500\ (PGA)^2 + 200\ (PGA) + 205 \qquad \text{(Eq. 1)}$$

Where,

Vs is the Threshold Shear Wave Velocity in m/sec and PGA is the Peak Ground Acceleration in the units of “g’s”.

It is also evident from Fig. 8 that the data plotting on or above the curve should be considered absolutely safe against liquefaction for a safety factor of 1.0 while that plotting below the curve should be treated as being vulnerable to liquefaction. Similar correlations can be developed for various liquefiable sand deposits for various safety factors.

Conclusions and Recommendations

1. In-situ shear wave velocity is an important parameter for evaluating low strain shear modulus, required for the dynamic design of sensitive structures. The same may be used for the quantitative assessment of ground liquefaction potential.
2. The gradation and densification of sand, peak ground acceleration (PGA), depth of groundwater table and the required factor of safety against liquefaction are the other main variables affecting the liquefaction potential, besides the shear wave velocity. The shear wave velocity, therefore, should not be used as a discrete variable to assess the liquefaction potential.
3. For submerged sand deposits, similar to Indus sands from gradation, densification and stress history point of view, a new procedure has been developed for the quantitative evaluation of liquefaction potential on the basis of shear wave velocity and the PGA, for a factor of safety of 1.0 against liquefaction. The simplified design chart thus developed is shown in Fig. 8.
4. The correlations / charts as in Fig. 8 can also be developed for other known liquefiable sites, for various safety factors.
5. The relationship presented in Fig. 8 and the like can be of great benefit to the geotechnical and structural engineering profession, as these afford a quick quantitative evaluation of the liquefaction potential of the ground on the basis of shear wave velocity.

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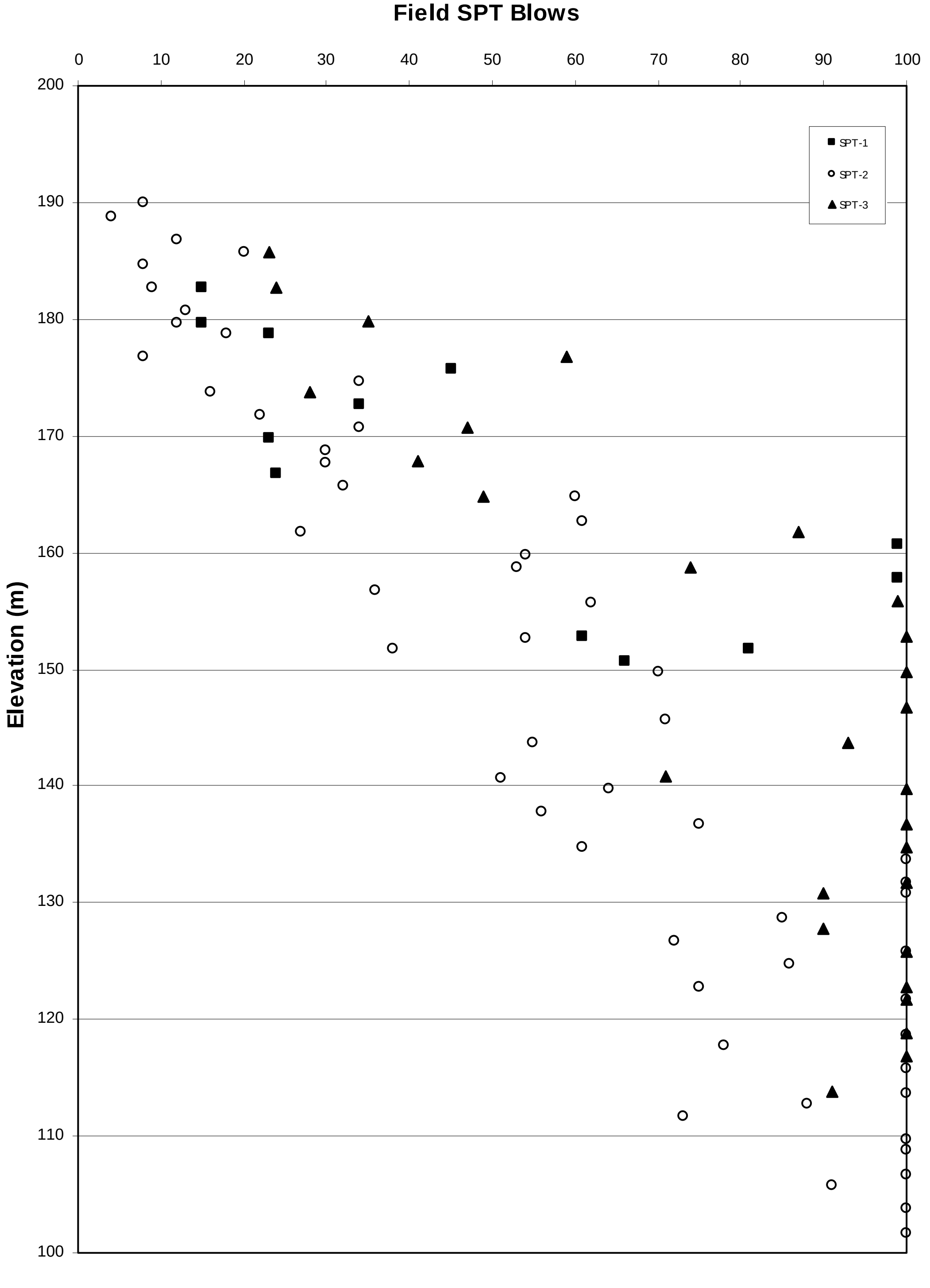

Figure 1. Variation of SPT " N $_{FIELD}$ "with elevation

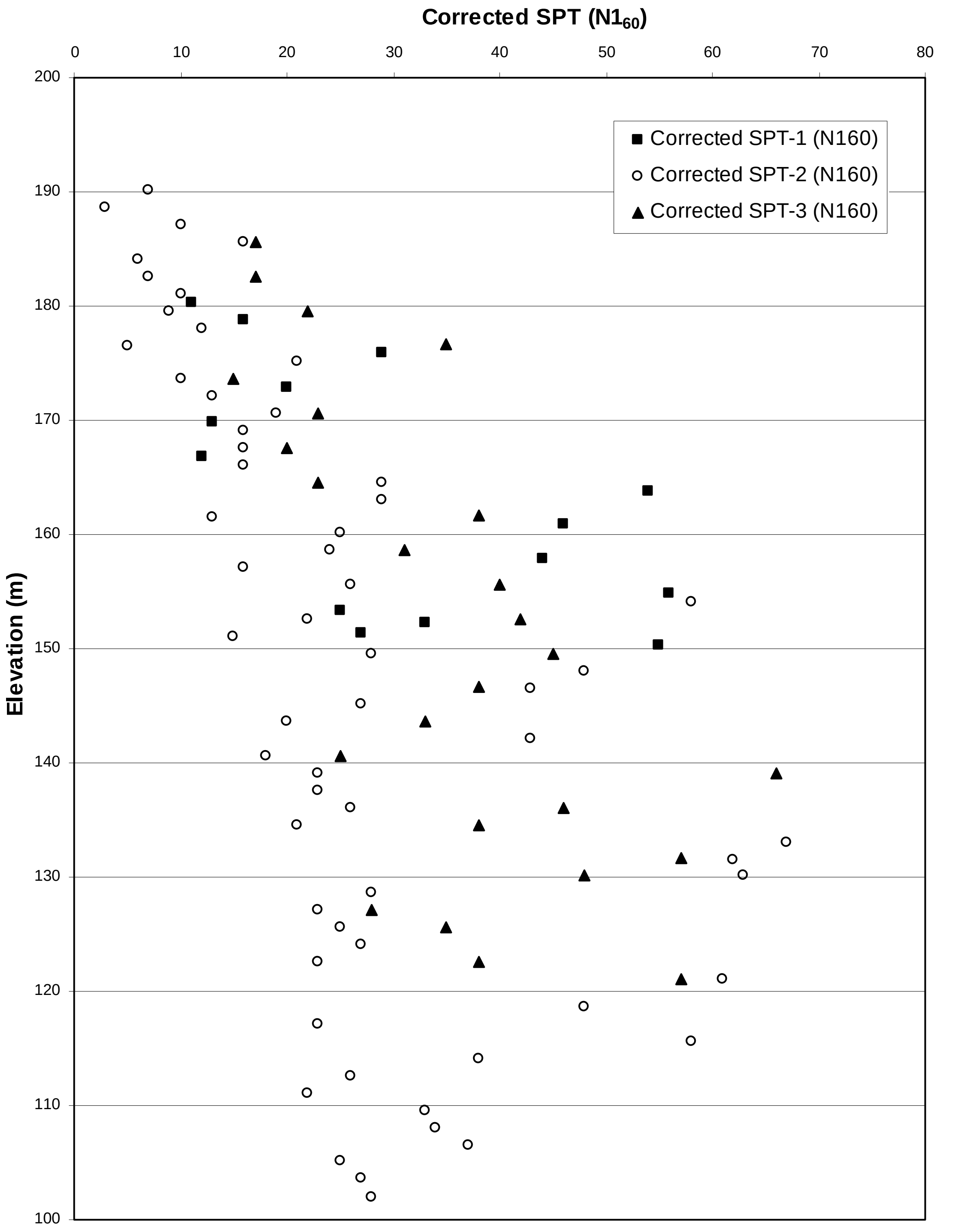

Figure 2. Variation of SPT " N $_{CORRECTED}$ " with elevation

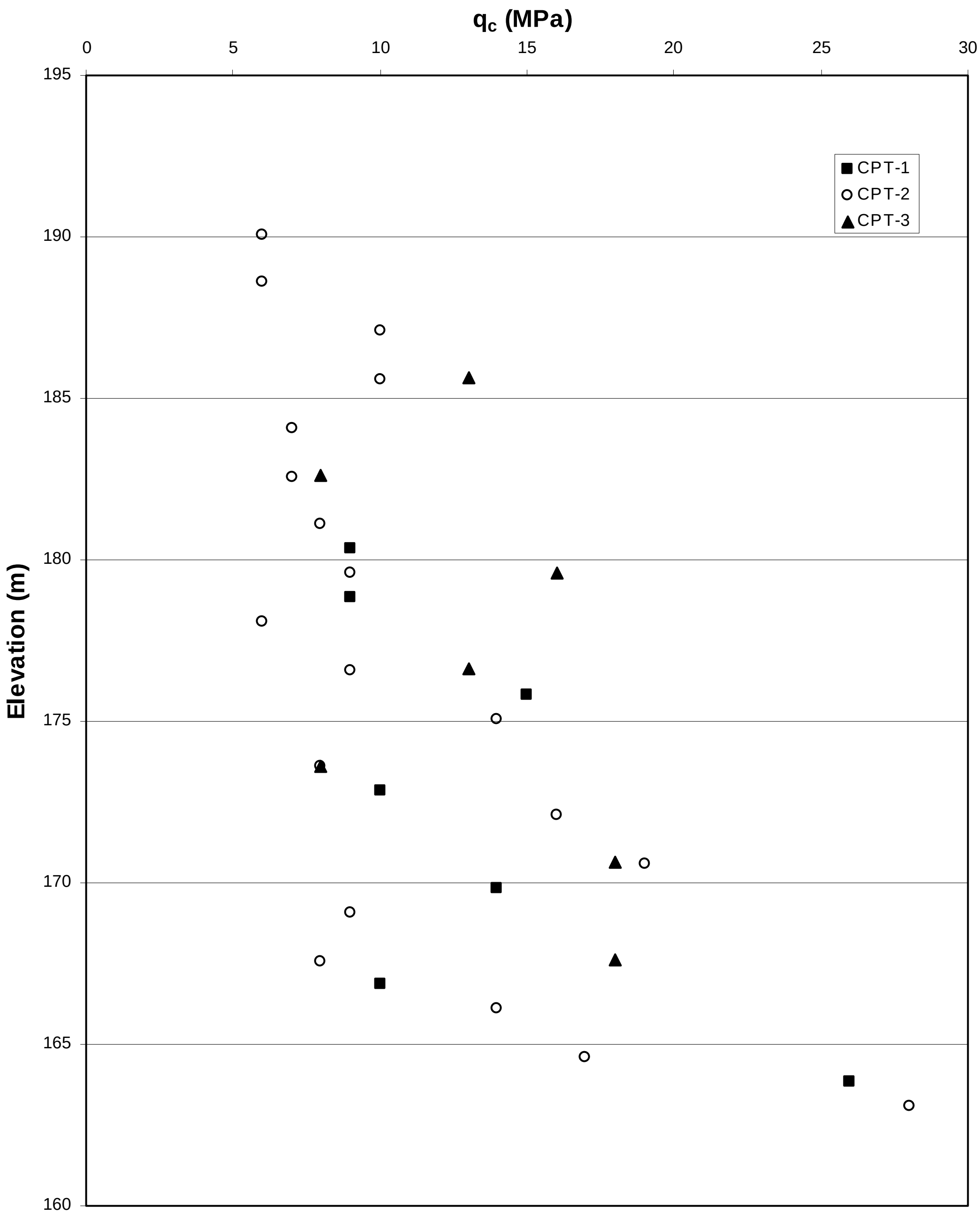

Figure 3. Variation of CPT tip resistance with elevation

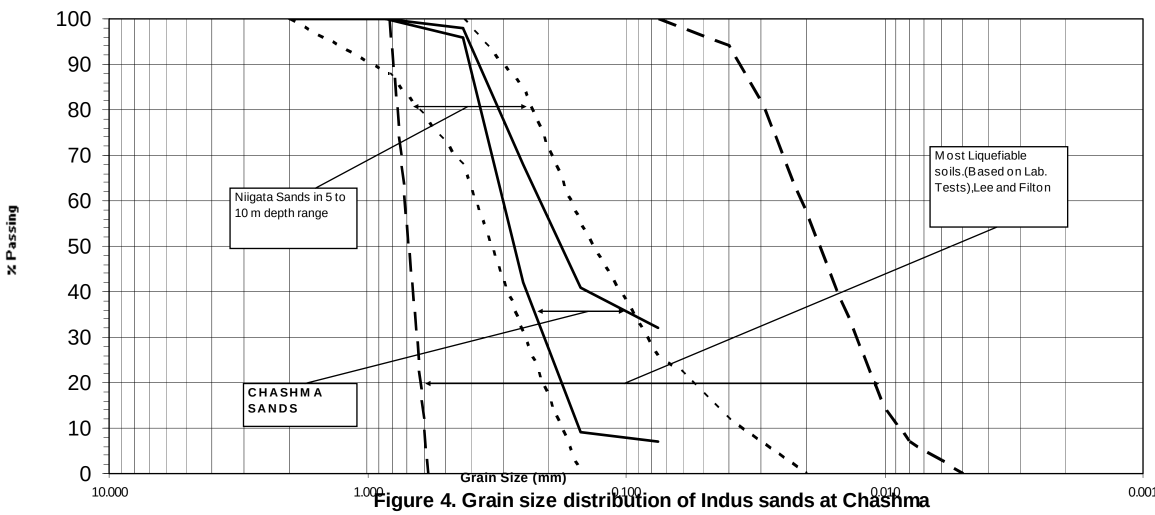

Figure 4. Grain size distribution of Indus sands at Chashma

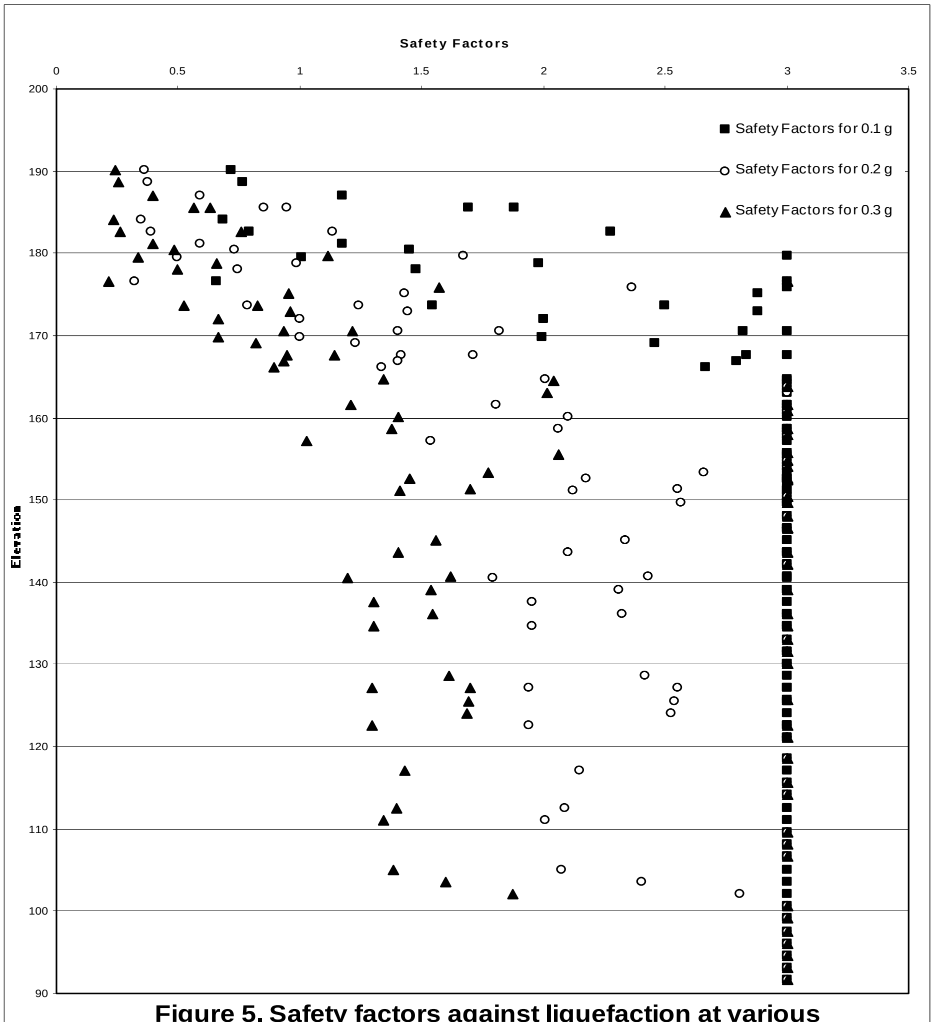

Figure 5. Safety factors against liquefaction at various levels

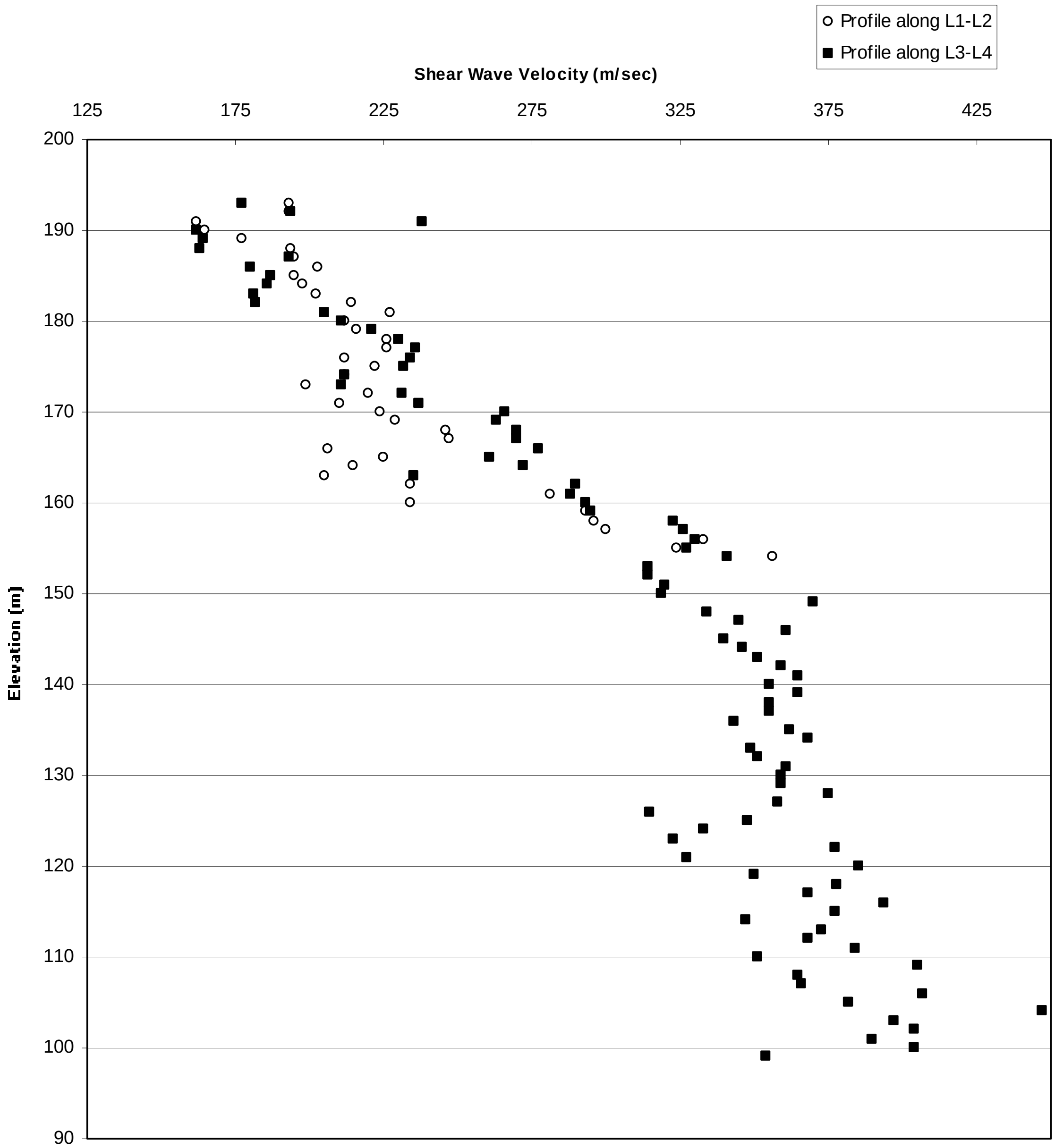

Figure 6. Shear Wave Velocity profile

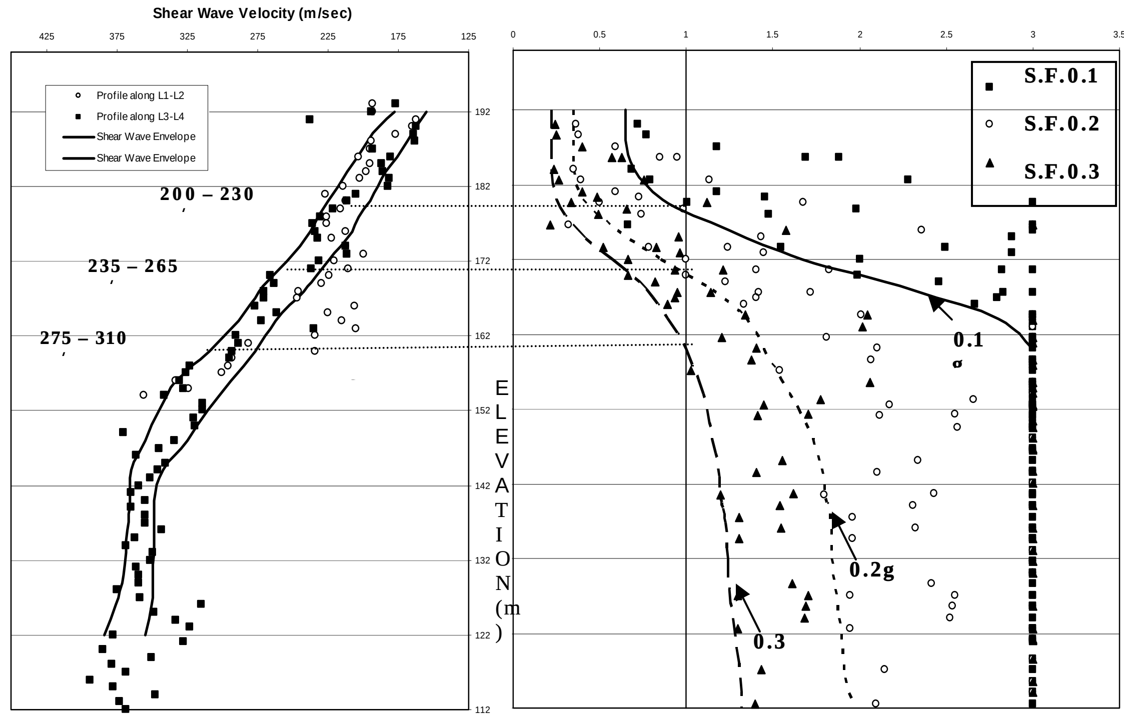

Figure 7. Lower limit safety factors against Shear Wave Velocity

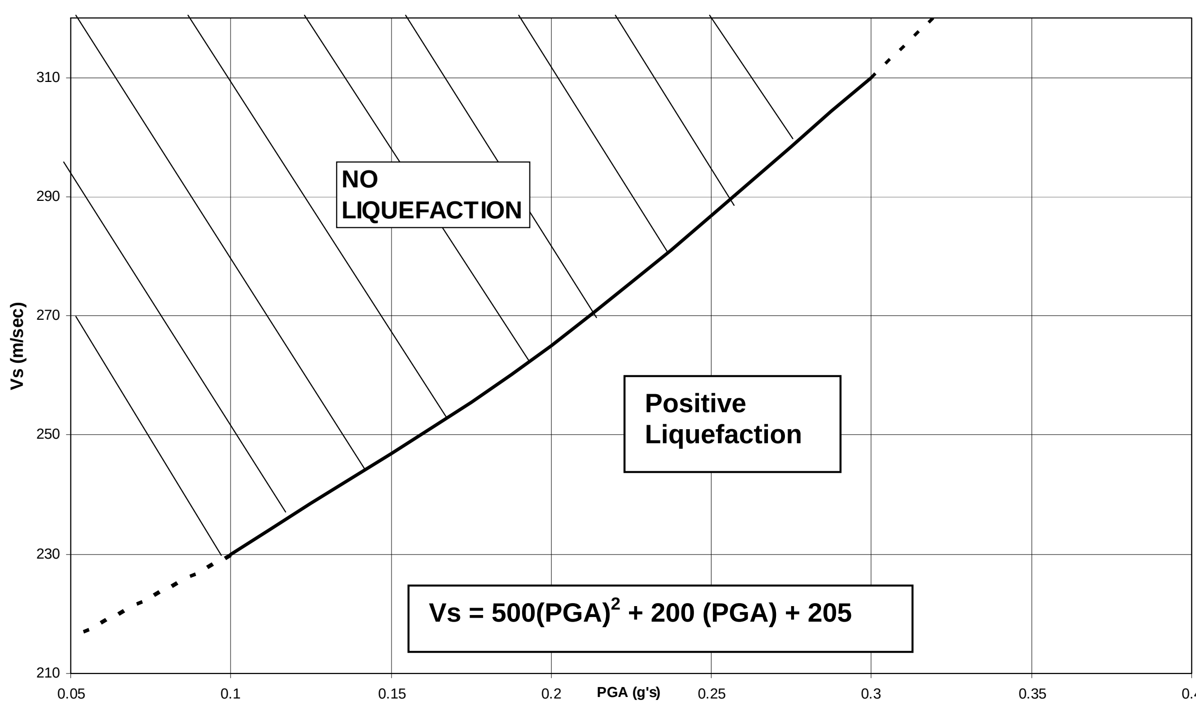

Fig. 8 Liquefaction design chart using Shear Wave Velocity & PGA