# Experimental research regarding the evaluation of the sand liquefaction sensibility using the cone penetration test

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***Abstract*—** The relationships between the cone penetration type resistance (CPT) and the liquefaction potential of sandy soils are presented to facilitate the use of CPT in liquefaction assessments. The proposed CPT – based relationships were developed to eliminate the need to rely on conversion of standard penetration test (SPT) blow counts to CPT type resistance used by existing CPT liquefaction potential relationships.

***Keywords*—** liquefaction, cone penetration, standard penetration, liquefaction potential.

## I. Introduction

WHEN assessing the liquefaction potential, the static cone penetration (CTP) presents a series of advantages as compared to the standard penetration (SPT), among which:

- it is more economical than SPT and allows a more complete research of the ground depth;
- it is a simple, more reproducible test than SPT;
- offers a continuous list of the ground resistances, which allows a good description of the geotechnical characteristics of the soil and the location of the liquefiable layers. This has a greater importance especially for sands and silty sands, due to the natural non-evenness of deposits.

Due to these advantages, it is preferable to obtain direct correlations between the penetration resistance ($R_p$) and the liquefaction potential, than the correlations based on standard penetration, by transforming them with the help of $R_p - N_{30}$ relations. This became possible due to the significant increase of the number of places with real liquefaction which are now available for cone penetrations tests.

The paper presents en empiric correlation for assessing the liquefaction potential, proposed by Stark and Olson (1995) [4], based on processing 180 cases of liquefaction and non-liquefaction which used data obtained by static penetrations.

The authors of this research used the correlation to assess the liquefaction sensibility of sandy soils on the site of objects belonging to CET Timisoara, based on experimental data obtained by static penetrations. It finally presents a relation which defines the liquefaction safety coefficient and its variation with depth.

## II. Proposed correlation (by Stark and Olson ) to assess the liquefaction potential

By processing 180 cases of liquefaction with data from static penetrations, Stark and Olson [4] proposed limitation fields which separate the liquefiable sites from non-liquefiable ones. The analyzed cases were divided in three groups according to the medium diameter ($D_{50}$) and the fines content (P.F.), as follows:

- clean sand: 0,25 mm < $D_{50}$ < 2,0 mm and P.F. ≤ 5 %;
- silty sand: 0,1 mm ≤ $D_{50}$ ≤ 0,25 mm and 5 % < P.F. < 35 %;
- sandy silt: $D_{50}$ < 0,1 mm and P.F. ≥ 35 %.

The fines content interests the granular fraction corresponding to silt and clay (max. 15 % clay).

The proposed limit fields define a relations between the normalized shear unitary stress (τ), mobilized during earthquake and the corrected penetration resistance ($R_{pl}$).

The normalized unitary shearing stress was determined using the simplified relation proposed by Seed and Idriss (1971), [1], [2].

According to this relation, the normalized unitary shear stress (τ), mobilized by the earthquake in any point of the pile is determined with the relation (1):

$$\tau = 0,65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \qquad (1)$$

where:

$a_{max}$ - maximum acceleration measured or assessed at the surface of the ground during earthquake;

g - gravitational acceleration (9,81 m/s$^2$);

$\sigma_{vo}$ - total unitary vertical stress;

$\sigma'_{vo}$ - real unitary vertical stress;

$r_d$ - correction depth factor.

The correction factor was estimated with the relation (2) for depths under 10 m:

$$r_d = 1 - 0,012 \cdot z \qquad (2)$$

where z is the depth in m.

Since most of the observations at the site showed that the liquefaction happened at a unitary stress ranging between 50 and 120 kPa, the penetration resistance must be corrected to correspond to a unitary vertical stress of about 100 kPa.

The corrected penetration resistance ($R_{pl}$) is determined with the relation (3), and the correction factor is determined with the relation (4) proposed by Seed et al. (1983), [3].

$$R_{pl} = R_p \cdot C_q \quad (3)$$

$$C_q = \frac{1{,}8}{0{,}8 + \left(\sigma'_{vo} / \sigma'_{ref}\right)} \quad (4)$$

where:

$C_q$ – correction factor;

$\sigma'_{ref}$ – reference unitary effort equal to 100 kPa.

The relations between the normalized unitary stress ($\tau$) and the corrected penetration resistance ($R_{pl}$), for the three analyzed categories of soil are shown in figures 1, 2 and 3.

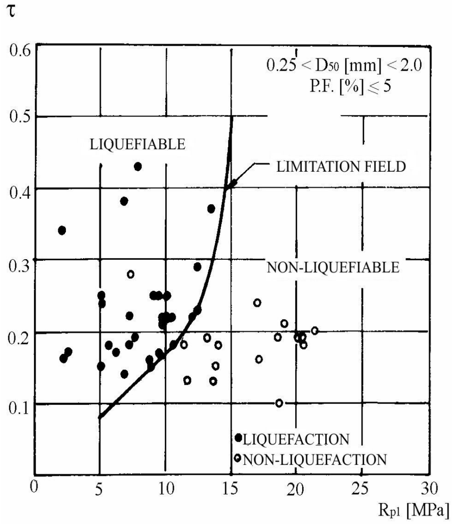


Fig. 1 - Relation $\tau$ - $R_{pl}$ for clean sand

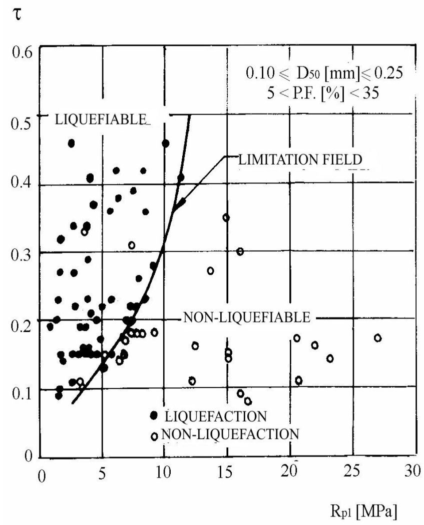


Fig. 2 - Relation $\tau$ - $R_{pl}$ for silty sand

Based on the observations at the sites with liquefaction or lack of liquefaction, the three limit fields were traced separating the liquefiable areas from the non-liquefiable ones.

The analysis of the data shown in figures 1, 2 and 3, we notice that there are few cases outside the proposed fields, the most being registered in the case of sandy silt (Fig. 3). These are exceptional cases where the site samples contain mostly fines, over 50 %, which leads to an increase of liquefaction resistance.

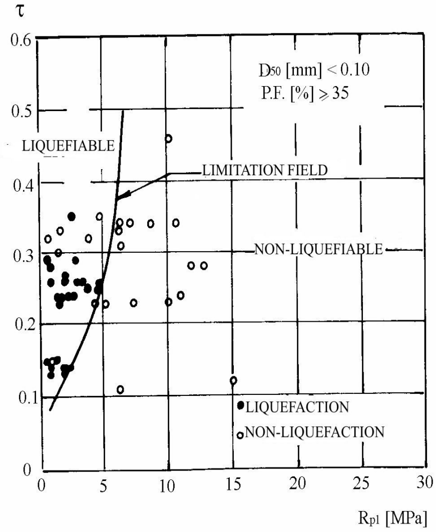


Fig. 3 - Relation $\tau$ - $R_{pl}$ for sandy silt

## III. Use of the proposed correlation on the site CET-Timişoara (Romania)

The proposed correlation was used to research the liquefaction susceptibility in sands on the site of objects belonging to CET Timisoara. The working way is shown for the objects STEAM BOILER and BUNKER BODY, analyzing the drills F 81 and F 10, respectively the penetrations PS 25 and PS 26. The profile of these drillings and the static penetration diagrams are presented in figure 4.

The ground stratification at the site is made up of a 1,60 m cover of topsoil and sandy or silt-sandy clay, under which there is a pack of fine and medium, medium and coarse or coarse sands, down to about 12,50 m. This sand pack is characterized by an average diameter ranging between 0,25…0,57 and fines contents under 5 %. The level of underground waters is 2,30…2,60 m from the natural ground level.

Table I centralizes the calculation of the normalized shearing stress ($\tau$) and the corrected penetration resistance ($R_{pl}$).

The calculation was horizontally led every meter, beginning under the level where the underground water was intercepted, using the relations (1)…(4).

The maximum acceleration ($a_{max}$) was estimated to $0{,}16 \cdot g$, corresponding to the seismic area D, according to the standard $P_{100\text{-}92}$ for the city of Timisoara.

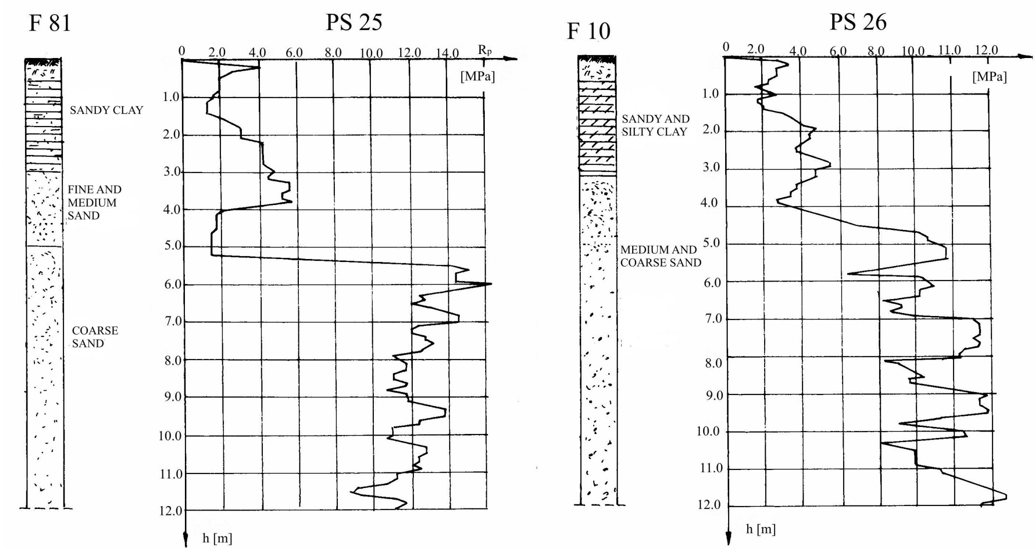


Fig. 4 – Drilling profile and static penetration diagrams.

Table I

| Site | Drill | Under-ground water level [m] | Calcu-lation level [kPa] | Total vertical unitary stress [kPa] | Real vertical unitary stress [kPa] | $R_p$ [MPa] | $C_q$ | $R_{pl}$ [MPa] | $a_{max}/g$ | $r_d$ | Normalized shearing unitary stress |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| STEAM BOILER AND BUNKER BODY | F 81 PS25 | 2,30 | 2,50 | 47,1 | 45,4 | 3,1 | 1,43 | 4,43 | 0,16 | 0,97 | 0,104 |
| | | | 3,50 | 65,7 | 54,0 | 5,0 | 1,34 | 6,70 | | 0,96 | 0,121 |
| | | | 4,50 | 84,4 | 62,6 | 1,8 | 1,26 | 2,27 | | 0,95 | 0,133 |
| | | | 5,50 | 103,1 | 71,3 | 8,5 | 1,19 | 10,11 | | 0,93 | 0,139 |
| | | | 6,50 | 121,8 | 80,1 | 12,4 | 1,12 | 13,88 | | 0,92 | 0,145 |
| | | | 7,50 | 140,5 | 88,9 | 12,2 | 1,06 | 12,93 | | 0,91 | 0,149 |
| | | | 8,50 | 159,2 | 97,7 | 11,3 | 1,01 | 11,41 | | 0,90 | 0,152 |
| | | | 9,50 | 177,9 | 106,4 | 13,8 | 0,97 | 13,38 | | 0,89 | 0,155 |
| | F 10 PS26 | 2,60 | 3,00 | 56,8 | 52,9 | 4,8 | 1,35 | 6,48 | 0,16 | 0,96 | 0,107 |
| | | | 4,00 | 75,9 | 62,1 | 3,6 | 1,27 | 4,87 | | 0,95 | 0,12 |
| | | | 5,00 | 95,0 | 71,35 | 11,3 | 1,19 | 13,45 | | 0,94 | 0,13 |
| | | | 6,00 | 114,1 | 80,6 | 10,7 | 1,12 | 12,04 | | 0,93 | 0,137 |
| | | | 7,00 | 133,2 | 89,85 | 13,0 | 1,06 | 13,78 | | 0,92 | 0,142 |
| | | | 8,00 | 152,3 | 99,1 | 11,0 | 1,005 | 11,05 | | 0,90 | 0,144 |
| | | | 9,00 | 171,4 | 108,35 | 13,8 | 0,96 | 13,23 | | 0,89 | 0,146 |
| | | | 10,00 | 190,5 | 117,6 | 12,6 | 0,91 | 11,46 | | 0,88 | 0,148 |

The pairs of values $\tau$ - $R_{pl}$, for each calculation horizon, were represented in figure 5, for PS 25, respectively the figure 6 for PS 26.

Figures 5 and 6 also represent the limit fields, which separates the liquefiable area from the non-liquefiable one, obtained in figure 1, for sands with 0,25 < $D_{50}$ < 2,0 mm and fines content under 5 %. The data obtained in figure 5 show that, the values $R_{pl}$ corresponding to the penetration PS 25 respectively the profile of the drilling F 81, three pairs of values $\tau$ - $R_{pl}$ are in the liquefiable area. It results that the soil is susceptible to liquefaction to the down to 5,50 m. From this depth down the soil becomes non-liquefiable, since all the pairs of values $\tau$ - $R_{pl}$ are on the right of the proposed limit field.

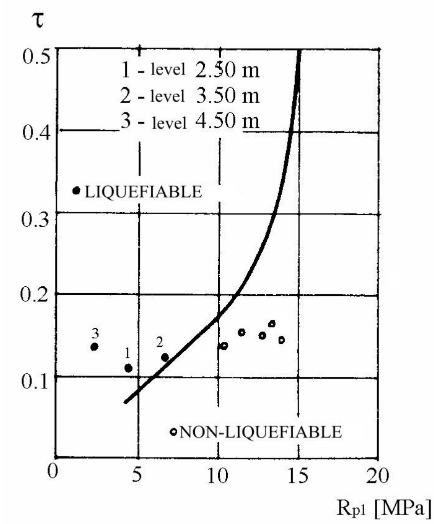


Fig. 5 – Processing of penetration PS 25

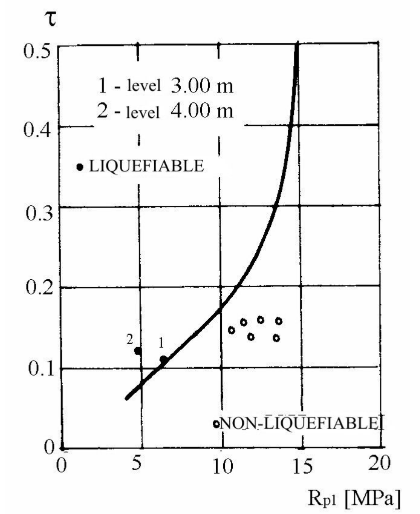


Fig. 6 – Processing of penetration PS 26

The data obtained from the procession of the penetration PS 26 and the drilling F 10 (Fig. 6), and using the same criterion, the soil results liquefiable down to 5,0 m, after which it becomes non-liquefiable.

The data processed in table 1 and figures 5 and 6 help determining the liquefaction safety coefficient defined by the relation:

$$F_l = \frac{\tau_l}{\tau} \quad (5)$$

where: τ - normalized shearing stress, mobilized by earthquake at calculation level;

$\tau_l$ – normalized shearing stress corresponding to the value $R_{pl}$, on the limit field, at the same level. The variation with the depth of the safety coefficient is shown in figure 7 for the two processed static penetrations.

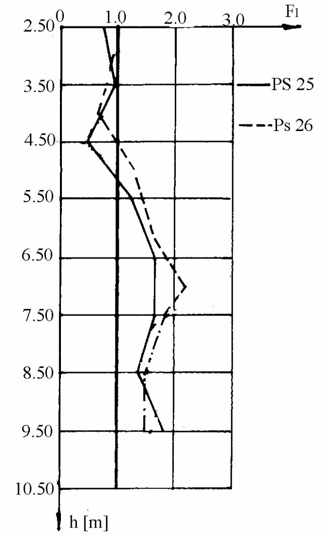


Fig. 7 – Variation of liquefaction safety coefficient

## IV. Conclusions

The cone static penetration can be beneficially used to assess the liquefaction potential of sandy soils, better than the standard penetration since is standardized, reproducible, economical and represents the continuous value of the penetration resistance in depth.

The empirical correlation used in the paper is base don real liquefaction cases, for which data was supplied by CET, and allows the direct use of static penetration for assessing the liquefaction susceptibility in sands, without needing transformation relations $R_p$ (CPT) in values $N_{30}$ (SPT).

The processing of the data available from drillings and static penetrations results in obtaining the value of the liquefaction safety coefficient, at any calculation level, which allows the localization of the layers susceptible to liquefy within the non-homogenous sandy deposits.

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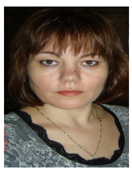

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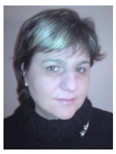

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