# Vibro compaction improvement of Tunisian liquefiable sands

## Amélioration par vibrocompactage de sables liquéfiables en Tunisie

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ABSTRACT

This paper presents the exploration of geotechnical conditions and interpretation of SPT and CPT results before and after soil densification using the vibrocompaction technique to minimize the hazard of liquefaction under the foundation of Sidi El Barrak earth dam in Tunisia. SPT control tests, confirmed by CPT data, showed significant improvement due to soil densification after vibrocompaction. Using correlations related to seismic hazard, it appears that the improved soil can prevent damages for earthquakes of magnitude at 0.15 g and 0.2 g.

RÉSUMÉ

Ce papier présente les conditions géotechniques et l'interprétation des résultats d'essais SPT et CPT réalisés avant et après densification du sol par vibrocompactage en vue de réduire le risque de liquéfaction sous la fondation du barrage en terre de Sidi El Barrak en Tunisie. Une amélioration significative due à la densification par vibrocompactage a été enregistrée à partir des résultats SPT qui sont confirmés par ceux de l'essai CPT. L'usage de corrélations spécifiques au risque sismique a permis de confirmer que les séismes d'intensité 0.15 g et 0.2 g ne devraient pas engendrer la liquéfaction du sol amélioré par vibrocompactage.

Keywords: loose sand, liquefaction, SPT, CPT, vibrocompaction, earth dam.

## 1. INTRODUCTION

Earthquakes may initiate simultaneous landslides and soil liquefaction. Based on the local geology, damage caused by earthquakes will vary from site to site. Problematic soil conditions exist in the north littoral of Tunisia primarily due to the seismic character of the area. The possibility of liquefaction of saturated fine sandy soil under the foundation of dams is high. In this regard the analysis of Sidi El Barrak earth dam, a large hydraulic project, provides an interesting case for evaluating the stability of the foundation. Because of the sandy nature of the dam foundation, special attention has been paid to evaluate the possible liquefaction potential that might occur. The liquefaction hazard was the primary reason for treatment of the foundation soil using the vibrocompaction technique.

Liquefaction phenomenon depends on several factors: namely the type of soil and its properties and the dynamic loading induced by earthquake (Seed, 1979; Roberston & Wride, 2000; Olsen & Stark, 2003; Sivrikaya & Togrol, 2006). Nigata's 1964 earthquake is certainly the event which brought internationally the attention of specialists in liquefaction. Since that time several research investigations have been conducted to well understand this phenomenon.

It has been followed by different methods suggested to geotechnical engineers for evaluating the hazard of liquefaction. These methods were based on correlation relating the liquefaction resistance and in situ tests results, mainly from SPT and CPT data (Roberston & Wride, 1998).

This paper presents, first, an overview about Sidi El Barrak dam and its soil of foundation. Then, the vibrocompaction treatment and related plot tests are detailed. From SPT and CPT results of tests conducted before and after improvement by vibrocompaction of foundation of Sidi El Barrak earth dam the liquefaction hazard is predicted and then discussed.

## 2. SITE OF PROJECT DAM

Sidi El Barrak earth dam is located at extreme North West of Tunisia in Beja governorate (Figure 1). The site of dam is distanced by 6.5 km to Mediterranean Sea, by 15 km to Nefza county and 20 km North East of Tabarka City (Technical document, 1990). Total area of dam is 4,000 hectares, and the reservoir level is equivalent to 29 m height. Total capacity of reservoir is about 275 Million cubic meters.

The heterogeneous foundation of dam is predominantly composed by sandy formations. These latter of Quaternaries, Neogene's and Palaeogene age consist in alluvial sand and wind dunes. The rigid stratum level is composed by gneiss and marlstone which are apparent at the right side (Figure 2).

For evaluating the liquefaction potential of soil foundation SPT and CPT data before and after improvement by vibrocompaction are analyzed.

The treatment of soil foundation, along about 10 m depth, has been executed in equilateral triangular zone of spacing 2.94 m. Figure 3 shows the location of zones where vibrocompaction treatment has been executed.

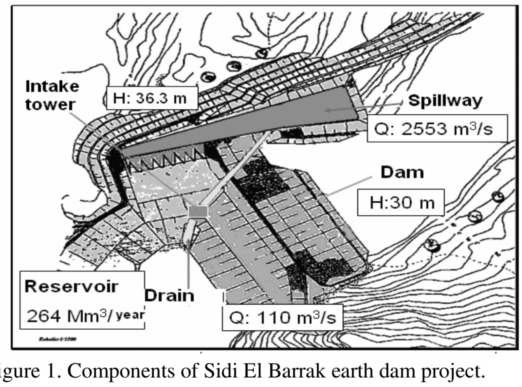


Figure 1. Components of Sidi El Barrak earth dam project.

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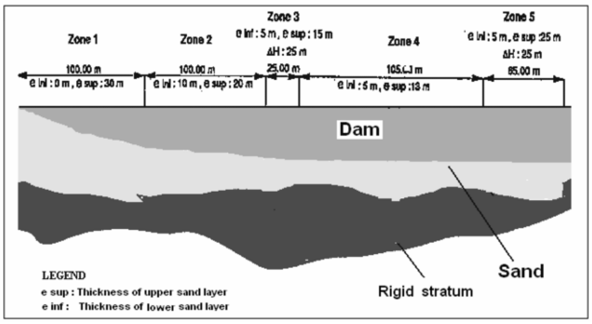


Figure 2. Geological section of the dam site.

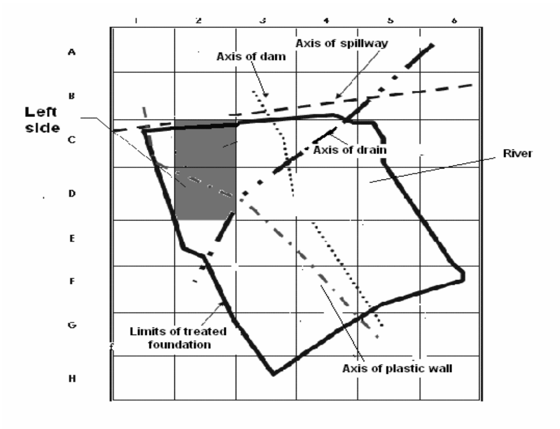


Figure 3. Vibrocompacted zones.

## 3. TREATMENT OF FOUNDATION

The geotechnical campaign in the site of dam aimed at geological, geotechnical and seismic investigation. Two wells executed respectively in zones C2 and D2 showed dominant blow sands (Figure 4). The location of two zones was decided based on lithology and hydrogeological characteristics of foundation. The water table level is at 5 m depth for the two zones. Recorded data and information collected have indicated, on one hand, the seismicity of dam area and, on the other hand, the loose state of soil foundation.

Indeed, it can be shown this configuration is generally the most unfavourable. Evaluating the liquefaction potential of the dam of foundation is made by adopting the reference equation which allows the prediction of corrected number of cycles as expressed by Trifunac & Brady (1975) and reported by Seed et al (1983):

$$N_{crit}= \tilde{N}.[1 + 0.125.(d_s - 3) + 0.05.(d_w - 2)] \quad (1)$$

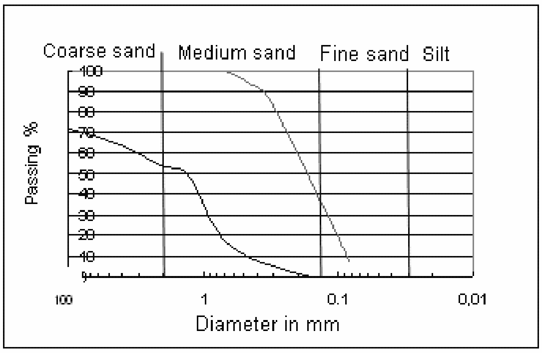


Figure 4. Grain-size distribution of soil in zone D2.

$d_s$ is the depth, from ground surface, in sand layer (m).
$d_w$ is the depth below upper level of water table (m).
$\tilde{N}$ is the number of cycles for penetration equals 30 cm, depending on earthquake magnitude.

Figures 5 and 6 show the variation in depth of corrected SPT blow count $N_{1(60)}$ and $N_{crit}$, for earthquakes of magnitude VII, VIII and IX in zone D2.

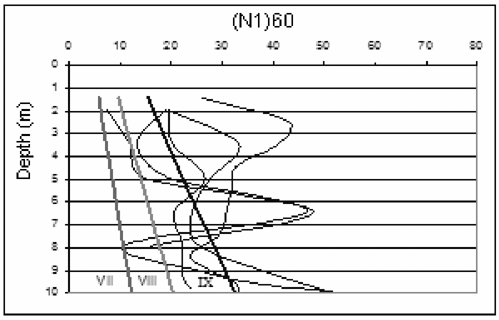


Figure 5. Pre treatment corrected Ñ values in zone D2.

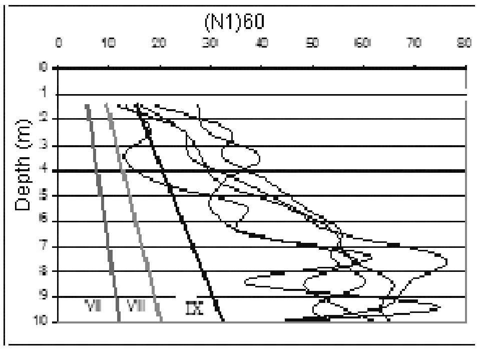


Figure 6. Post treatment corrected SPT values in zone D2.

The liquefaction hazard can also be evaluated from CPT results. Zhou, 1980 (in Seed et al, 1983) had considered such data to identify the liquefaction potential from the formula:

$$q_{crit}= q_{c0} .[1 - 0.065.(z_w - 2)].[1 - 0.005.(z_s - 2)] \quad (2)$$

$q_{crit}$ is the critical resistance under which liquefaction hazard is potential.
$q_{c0}$ is the static penetration resistance that depends on epicentral intensity of considered earthquake (Table 3).

Table 3: Static penetration $q_{c0}$ as a function of earthquake. magnitude and acceleration

| Magnitude | Acceleration | $q_{c0}$ (MPa) |
|---|---|---|
| VII | 0.15g | 8.2 |
| VIII | 0.2g | 11.7 |
| IX | 0.4 g | 18.0 |

$z_w$ and $z_s$ are respectively the depth of water table level from ground surface and the distance between water table level and point of measurement (in meters).

Based on cone penetration resistance data before vibrocompaction and threshold curves given by Zhou (1980) from equation (1) for 0.15 g and 0.2 g accelerations (respective $q_{c0}$ are 8.2 MPa and 11.7 MPa) Figure 7 shows the distribution of points of measurements of $q_{c0}$ as a function of depth below the two curves of reference. This latter illustrate weak penetration resistance within two investigated zones C2 and D2. It can be seen (Figure 8) the existence of liquefaction hazard for earthquake with magnitude 0.2 g and, with more less influence for earthquake with magnitude 0.15 g.

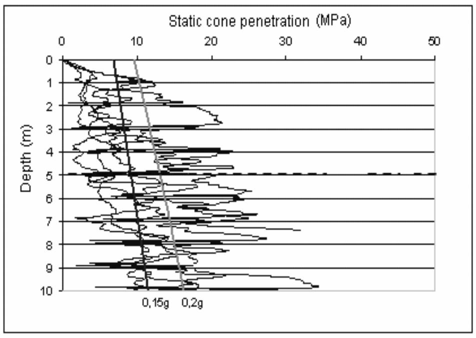


Figure 7. Pre treatment recorded CPT data in zone C2.

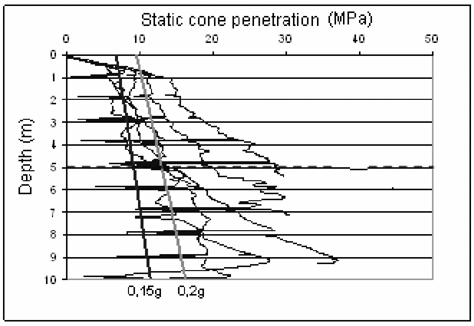


Figure 8. Post treatment recorded CPT data in zone C2.

## 5. EVALUATING THE EFFICIENCY OF VIBRO COMPACTION FROM SPT AND CPT DATA

The efficiency of vibrocompaction treatment is evaluated through comparisons between SPT or CPT data recorded after treatment and the curves of reference which limit the domain of liquefaction hazard for given earthquake magnitudes. For Sidi El Barrak dam project both SPT and CPT were executed to give much more assessment of predictions and to conclude about the efficiency of vibrocompaction technique in the investigated site.

### 5.1 *SPT Data*

The evaluation of treatment efficiency is intended for earthquakes of magnitudes VII, VIII and IX. Recorded SPT data after treatment in zone D2 has shown a significant improved dynamic penetration resistance recorded from SPT investigation for earthquake of magnitude VII. While for earthquakes of magnitude VIII and IX which are less expected in the site of dam most points of measurements indicate the concurrency of critical situation is few likely.

Seed and Idriss (1971) had introduced the concept of cyclic stress ratio (CSR) due to earthquake $\tau_{av}/\sigma'_v$ in view of dissociating, based on SPT data, between the liquefaction and non liquefaction conditions. The CSR is defined by:

$$CSR = (\tau_{av}/\sigma'_v) = 0.65 \cdot (\sigma_v/\sigma'_v).(a_{max}/g) \cdot r_d \qquad (3)$$

$\sigma_v$ and $\sigma'_v$ are total overburden stress and vertical effective stress at considered depth. $\tau_{av}$ is the averaged shear stress induced by earthquake at the same depth.
$a_{max}$ is the peak ground acceleration;
g is the gravity acceleration;
$r_d$ is the stress reduction factor with depth.

Figure 9 represents the cyclic stress ratio (CSR) induced by earthquake as a function of SPT data recorded before and after treatment. Substantial soil improvement is observed from SPT records after soil vibrocompaction. This result confirms the predictions illustrated in Figure 6.

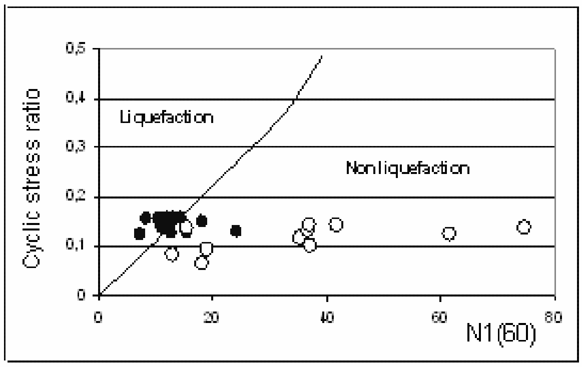


Figure 9. Correlated CSR-corrected SPT records in zone D2.

In exploited SPT data it was taken into account of the depth of considered sand layer and water table level from ground surface as well as of the earthquake intensity. Contrarily grain size and effective stress were not taken into account; however such soil structure characteristics have significant influence on cyclic resistance. For this purpose the undrained cyclic resistance, deduced from triaxial tests results, was correlated to in situ characteristics i.e. SPT value, effective stress and mean diameter $d_{50}$ of sand grains. Corte (1982) had proposed a correlation between the cyclic resistance $\tau/\sigma'_v$ with grain size and the magnitude of earthquake. This correlation writes:

$$(\tau/\sigma'_v) = A. [(N_{1(60)}/(\sigma'_v + 70))^{0.5} - 0.258 \log(d_{50}/0.35)] \qquad (4)$$

Where $\sigma'_v$ unit is kPa. The condition: $0.04 \text{ mm} \leq d_{50} \leq 0.6 \text{ mm}$ should be fulfilled. After Corté (1982) A is a coefficient which characterizes the influence of earthquake magnitude on resistance of liquefaction. The non liquefaction condition is:

$$\tau_{av}/\sigma'_v < \tau/\sigma'_v \qquad (5)$$

From Figure 10 which illustrates the variation of CSR induced by earthquake as function of the cyclic resistance $\tau/\sigma'_v$ it is well noticed how significant is the influence of vibrocompaction on the cyclic resistance of soil.

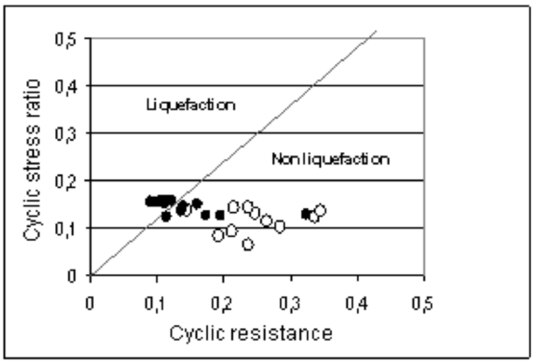


Figure 10. Evolution of CSR vs cyclic resistance in zone D2.

## 5.2 *CPT Data*

Comparing between CPT data recorded before and after vibrocompaction treatment should give better assessment of treatment efficiency. Figure 11 well shows the soil improvement recorded in zone C2 after vibrocompaction as the static penetration resistance of soil has greatly increased for earthquakes of magnitudes 0.15 g and 0.2 g. The curve of reference corresponds to earthquake intensity VIII.

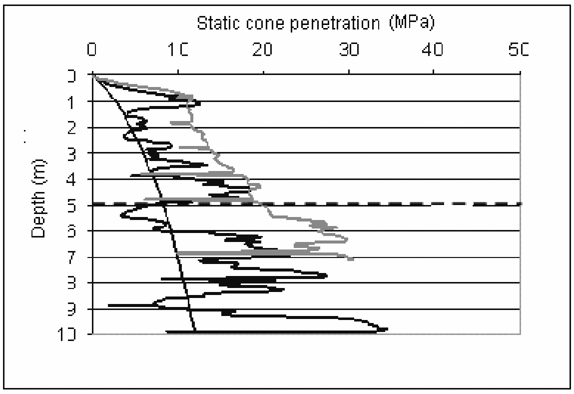


Figure 11. Post treatment recorded CPT data in zone C2.

The influence of water table level on soil liquefaction had investigated by Schmertmann (1978), cited in Seed et al (1983), after experimental investigation on fine sands, with different relative densities, and subjected to cone penetration tests. From this work a correlation had been suggested to estimate the corrected tip resistance ($Q_c$) as follows:

$$Q_c = q_{c0} \,.\, C_0 \, (\sigma'_v)^{C1} \exp(C_2 \,.\, D_r) \qquad (6)$$

Where $C_0 = 12.31$; $C_1 = 0.71$ and $C_2 = 2.91$.
$D_r$ is the relative density in percentage.

As Schmertmann correlation depends on effective vertical stress, consequently the water table level is taken into account. Comparing between records, in zone C2, before and after treatment well show the soil improvement due to vibrocompaction since quasi total reduction of liquefaction hazard is guaranteed. Meanwhile it is noticed the significant decrease of cone penetration resistance at 7 m depth due the increase of pore water pressure from which follows the decrease of vertical effective stress.

## 6. CONCLUSIONS

The stability of the soil foundation of Sidi El Barrak dam project has been analyzed with respect to liquefaction hazard which may occur during earthquakes. The vibrocompaction as improvement technique has been adopted to enhance mechanical characteristics of soil foundation. Then the efficiency of soil treatment was evaluated after comparing between SPT and CPT recorded data pre and post vibrocompaction improvement.

In two investigated zones very significant cyclic resistance was predicted for earthquake intensity VII. While for earthquakes intensities VIII and IX SPT records showed up the critical condition of reference was exceeded in several points and, consequently, the treatment of the foundation does not take account of the conditions of such earthquake intensity.

Although CPT records have mostly confirmed the predictions from SPT data it was highlighted the influence of pore water pressure in decreased static resistance of improved soil under water table level. All correlation used revealed satisfactory especially for evaluating the efficiency of improved fine sand by vibrocompaction technique in view of prevention of liquefaction.

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