COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

NUMERICAL SIMULATIONS OF LIQUEFACTION PHENOMENA AFTER EMILIA ROMAGNA (20 MAY 2012) EARTHQUAKE

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Keywords: Earthquake Engineering, Liquefaction, Emilia Romagna Earthquake (20 May 2012), Numerical simulations, OpenSees PL.

Abstract. *Soil liquefaction has been observed worldwide during earthquakes with induced effects responsible for damage, disruption of function and considerable replacement expenses for structures. The May 20, 2012 M5.9 shock in Emilia Romagna (Italy), is one example of moderate earthquakes yielding extensive liquefaction-related phenomena. The paper provides an attempt to simulate the observed ground effects using a finite element (FE) approach. The study adopts a FE computational interface (OPENSEES PL) implemented in OpenSees and able to analyze the earthquake-induced three-dimensional pore pressure generation. Credited non-linear theories are applied in order to take into account appropriate flow rules as to reproduce the observed strong dilation tendency and resulting increase in cyclic shear stiffness and strength. The interface simplifies the 3D spatial soil domain, boundary conditions and input seismic excitation definition with convenient post-processing and graphical visualization of analysis results including deformed ground response time histories. The possibility to simulate wave propagation adopting realistic boundaries is of particular importance and significance in order to realistically reproduce liquefaction behaviour.*

1 INTRODUCTION

The seismic sequence that in May 2012 struck a large area of the river Po Valley (Emilia-Romagna region, Northern Italy) and led to collapse many industrial buildings, churches, bell towers and more than ten thousand residential constructions [1], also triggered significant fractures and deformations in a number of riverbanks located close to the earthquake epicenter.

Among them, one of the most severely damaged structures turned out to be the banks of an irrigation canal known as *Canale Diversivo di Burana*, flowing through the small village of Scortichino (Municipality of Bondeno), near the historic town of Ferrara (Figure 1). Large, longitudinally-oriented ground cracks were observed along a 3 km bank stretch, causing in turn severe structural damages to a large part of the approximately one hundred houses and productive activities built on the bank crown. At the same time, it was observed that the deformation phenomena did not equally affect the bank over its entire length, being the seismic-induced fracture system particularly evident in the four main areas labelled as A, B, C and D in Figure 1.

This study is based on the large experimental database collected in the context of an extensive study carried out by a number of research groups from various Italian universities in co-operation with technical experts of the Geological, Seismic and Soil Survey Regional Department. The paper provides an attempt to simulate the observed ground effects using a finite element (FE) approach together with an advanced constitutive formulation developed within a multi-surface plasticity framework for modelling of cyclic behavior in saturated sands.

In this regards, FE analysis allows modelling the distribution of effective stress, pore pressure, strain and permanent displacements, thus providing an accurate description of the subsoil response and failure mechanisms. In particular, the study adopts a FE computational interface (OPENSEES PL) implemented in OpenSees [2] based on a three-dimensional formulation as to reproduce the observed strong dilation tendency and resulting increase in cyclic shear stiffness and strength.

Figure 1. Aerial view of the Canale Diversivo di Burana, with location of the investigated areas.

2 GEOTECHNICAL BACKGROUND

Geotechnical characterization of the Canale Diversivo riverbank and the relevant foundation soil was based on a comprehensive experimental program including both in situ and high-quality laboratory tests. Figure 2 shows results from one of the piezocone tests (CPTU) carried out from the top of the bank, in area C, together with the soil stratigraphy detected from an adjacent borehole (S3). Profiles of the corrected cone resistance q_t, sleeve friction f_s and pore pressure *u* detail a well-defined 9 m thick, rather heterogeneous top layer of alternating sands, silty sands and sandy silts, partly forming the artificial riverbank (*Unit R*, upper 5 m), partly referable to the flood plain environment (lower 5 m, *Unit B*). A fine-grained stratigraphic unit (*C*), mainly composed of clay-silty clay, can be then identified from 9 to 12 m in depth, followed by a medium-coarse sandy layer forming the so-called *Acquifero Padano* (*Unit A*), which was almost continuously detected down to a depth of 50 m. A thin interbedded clayey lens, similar to *Unit C*, was encountered at depths between 29 and 32 m from the top of the embankment. Details on the whole laboratory testing results, including cyclic resistance curves of coarse grained soils and modulus reduction curves *G*-γ, can be found in [3].

Application of some well-known interpretation procedures, based on either piezocone data or dilatometer results, for the cyclic liquefaction susceptibility assessment, showed that a large part of *Unit B* is very likely to have experienced liquefaction phenomena for an earthquake moment-magnitude equal to the May 2012 main event (M_w = 6.1). By contrast, *Unit A* was generally found not susceptible to cyclic liquefaction.

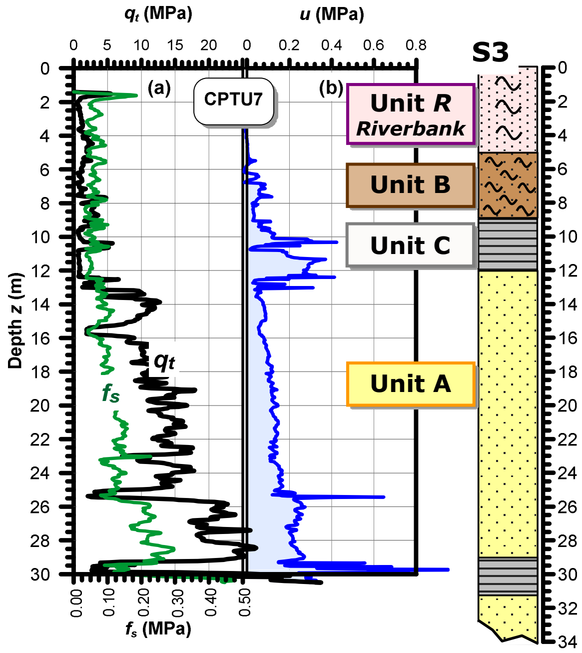

Figure 2. CPTU 7 log profiles compared with the soil column obtained from the nearby borehole S3.

3 COSTITUTIVE FORMULATION

In this study the mechanical behavior of cohesionless soil units *R*, *B* and *A* has been described in terms of an advanced constitutive formulation developed within the framework of multi-yield-surface plasticity for numerical simulations of cyclic liquefaction response and associated accumulation of cyclic shear deformation observed in clean sands and silts. This model [4, 5, 6] is based on a conical yield surface in principal stress space, with the hardening zone defined by a number of similar yield surfaces having a common apex along the hydrostatic axis. The outermost surface is given by the failure locus, related to the shear strength angle ϕ'. Moreover, in order to properly reproduce the phenomenological interaction between shear and volume changes in sands and the associated cyclic mobility mechanisms, the deviatoric component of the flow rule was assumed as associate, non-associativity being solely restricted to the volumetric component. A detailed description of constitutive equations as well as of the parameter calibration can be found in [4, 5, 6]. The model requires the definition of the soil peak friction angle and the associated shear strain, together with the G-γ curve and a set of dilatancy/liquefaction parameters governing the rate of shear-induced volume changes/pore pressure development and the plastic shear strain accumulation.

The clayey Unit C has been treated as a nonlinear hysteretic material, using a Von Mises multi-surface kinematic plasticity approach together with an associate flow rule. This constitutive formulation is able to capture both monotonic and hysteretic elasto-plastic cyclic response of those soils whose shear behavior is assumed insensitive to confining stress. According to this formulation, plasticity is exhibited only in the deviatoric stress-strain response, while the volumetric response is linear-elastic.

4 FINITE ELEMENT MODEL

Numerical model of the riverbank aims at reproducing a more detailed insight into the seismic-induced pore pressure response and displacement development of the silty-sandy sediments, applying a versatile constitutive approach in conjunction with a fully coupled two-phase formulation. In particular, the aim is to reproduce the seismic response of a soil column corresponding to the stratigraphic conditions provided by borehole S3 (Figure 2), applying the open-source computational interface OpenSeesPL, implemented within the FE code OpenSees [2]. This platform consists of a framework for saturated soil response as a two-phase material following the u-p (where u is displacement of the soil skeleton and p is pore pressure) formulation [7, 8]. The 3D soil domain is represented by 20-8 nodes, effective stress fully coupled (solid-fluid) brick elements [2] built up with 20 nodes in order to describe the solid translational degrees of freedom and the eight-corner nodes for the fluid pressure [9]. The interface used in this study, originally calibrated for pile analyses was modified in order to take into account free field response [9].

Figure 3 shows the adopted 3D 40m × 40m x 120m FE mesh, composed of 792 brickUP, linear isoparametric 8 node elements with 1036 nodes. The model base boundary, set at a depth of 120 m from ground surface, corresponds to the top of the bedrock, whose position could be identified from velocity measurements provided by cross-hole tests. Opensees ability to simulate the real wave propagation adopting realistic boundaries is of particular importance in order to realistically reproduce the above scenarios. Assuming that at any special location, symmetry conditions can be adopted, periodic boundaries [10] have been considered. Therefore, displacement degrees of freedom of the left and right boundary nodes were tied together both longitudinally and vertically using the penalty method. In this regards, base and lateral boundaries were modelled to be impervious, as to represent a small section of a presumably infinite (or at least very large) soil domain by allowing the seismic energy to be removed from the site itself (for more details, see previous studies such as [11, 12]).

A seismic excitation was defined along the base in the longitudinal direction (x-axis), taking the main shock (M_w = 6.1) occurred on May 20th as reference event. In the absence of any strong motion station located in the area of Scortichino, a number of appropriate input motions were selected from the *Italian Accelerometric Archive* (ITACA, [13]), having moment magnitude M_w 5.50 to 6.50 and epicentral distance in the range 5÷10 km [3]. In this paper, only results of the analyses based on the east-west (E-W) acceleration record from the Cascia site during the 1979 Val Nerina (Italy) earthquake (Figure 4) are discussed.

Table 1 summarizes the values adopted for material parameters, most of these derived from the available experimental data. However, a general difficulty was encountered in defining some of the so-called dilatancy/liquefaction model coefficients, hence values suggested from the literature [9] were preliminary adopted and a sensitive study was carried out in order to identify the most appropriate set of material parameters. Particular attention was focused on parameters calibration of Unit B, where significant pore pressure build-up and permanent shear strain accumulation presumably gave rise to the observed ground surface effects. Such unit, similarly to the riverbank sediments (R), was modelled as medium-loose coarse soil layer, while the deep unit A was treated as dense sand.

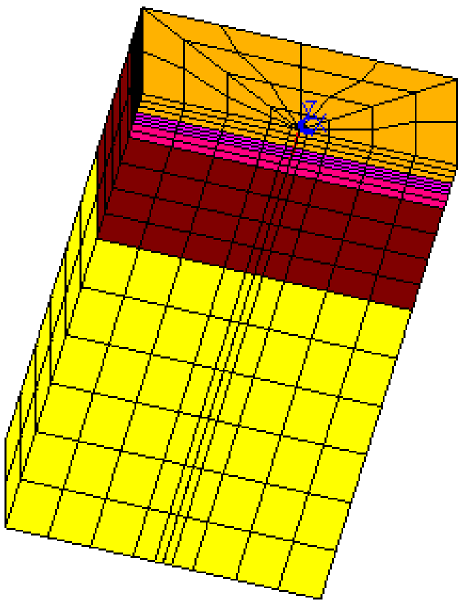

Figure 3. FE model.

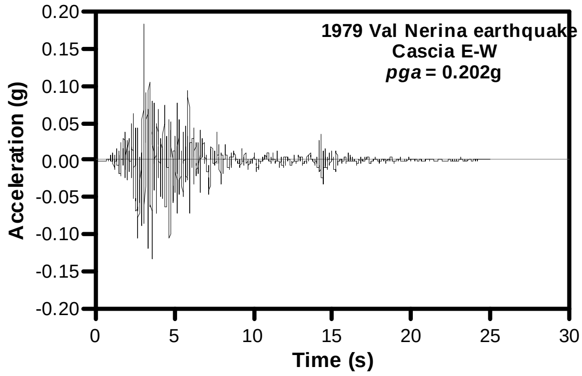

Figure 4. Acceleration time history adopted in the FE analysis.

Soil parameters	Unit R	Unit B	Unit A
ϕ'_{peak} (°)	34	30	34
c_1	0.07	0.15	0.07
d_1	0.4	0.4	0.4
d_2	2	2	2
l_1	10	10	10
l_2	0.01	0.01	0.01
l_3	1	1	1

Table 1. Pressure-dependent multi-yield model parameters.

5 FINITE ELEMENT RESULTS

Figure 5 shows excess pore pressures time histories at relevant depths (5-8 m) in order to study saturated *Unit B* response. The graph clearly shows that significant excess pore pressures develop during seismic excitation and that a maximum constant value is finally attained at each depth. Furthermore, there is no evidence of dissipation phenomena in the 10 seconds after the input motion duration.

The associated R_u values (approximately equal to 0.60 - 0.65) turn out to be in substantial agreement with the estimate of R_u (0.75) obtained from the interpretation of cyclic simple shear tests on the basis of prudential assumptions, i.e. taking into account the combined effect on pore pressure build-up of multiple aftershocks and fully undrained conditions.

Figure 6 shows lateral displacement time history at ground surface and provides immediate evidence of a gradual accumulation of permanent deformations. Time history shows a periodic shape with lateral displacements oscillating around zero. Figure 6 shows in red line that the permanent mean value is equal to 2.6 cm. Such predicted response, computed at the ground surface, is fully consistent with the observed seismic-induced cracks on the riverbank crest. Figure 7 shows that all the lateral spread is concentrated between 5 and 8 m depth (unit B). Therefore, lateral spread does not affect superficial layer (unit R).

The interface allows to show 3D mesh deformation. Figure 8 represents 3D full mesh in correspondence of the maximum longitudinal displacements (t = 7.80 sec). In particular, lateral displacements values are around 5 cm in the deepest layers and 2 cm in the superficial 12 m layers. The corresponding mean deformation result 0.05% and 0.16% respectively. These values show a good agreement with the in situ tests response. Figure 9 details the superficial layers in order to show how they translate rigidly on the lower as a rigid body.

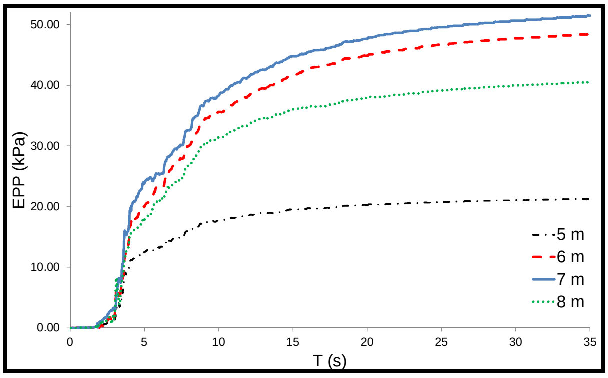

Figure 5. Excess pore pressures time histories at various depths.

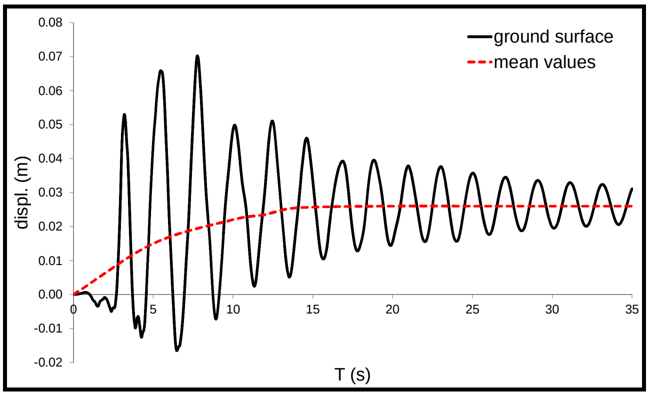

Figure 6. Lateral displacement time histories at ground level.

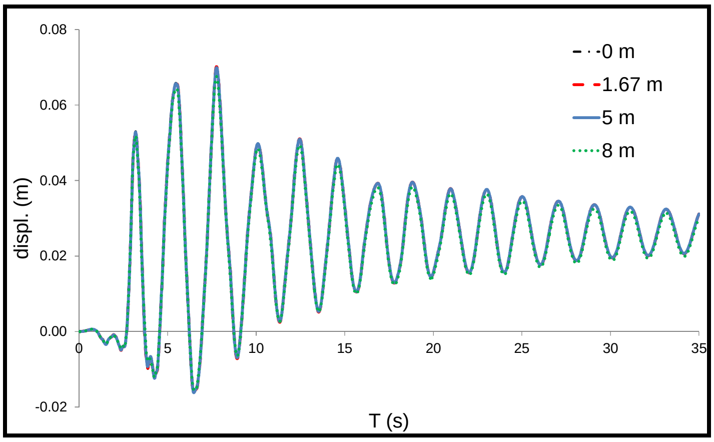

Figure 7. Lateral displacement time histories in the superficial layer (Unit R).

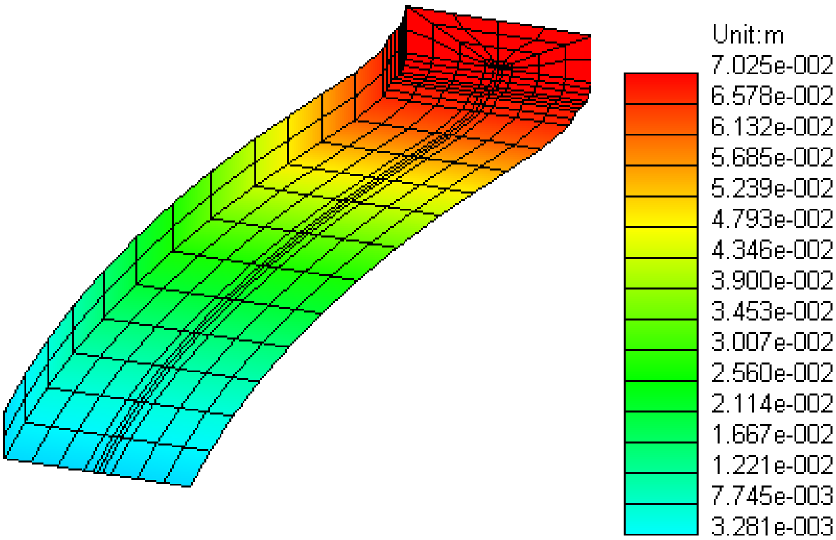

Figure 8. 3D mesh: maximum lateral displacement at 7.80 s (scale: 1:1000).

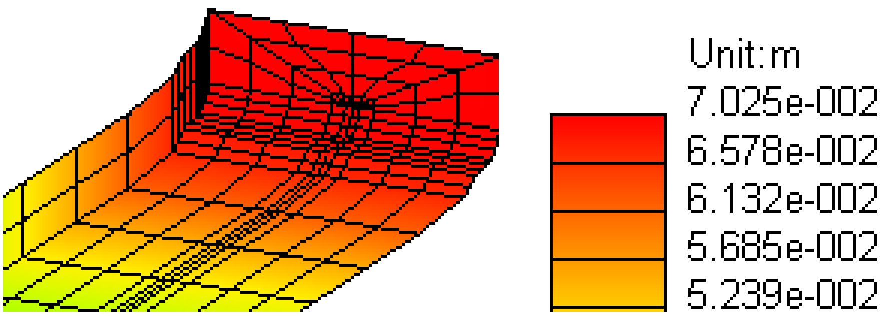

Figure 9. 3D mesh (particular): maximum lateral top displacement at 7.80 s (scale: 1:1000).

6 CONCLUSIONS

The paper shows a numerical study aimed at assessing the seismic response of a riverbank severely damaged by the May 2012 Emilia-Romagna earthquake, adopting OpenSeesPL. The FE computational platform is based on an advanced constitutive formulation specifically intended for describing granular soil behaviour in cyclic loading conditions and thus liquefaction phenomena.

Numerical results have shown that during seismic excitation saturated silty sands of the riverbank subsoil developed significant excess pore pressures and permanent deformations. The proposed FE model confirmed the main observed ground effects at the riverbank surface, consisting in typical lateral spreading phenomena.

According to the presented results, this study may be considered the first step for the development of a detailed FE model of the entire riverbank, accounting for the real topography of the ground structure.

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