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STUDY OF THE DYNAMIC SOIL-ABUTMENT-SUPERSTRUCTURE INTERACTION FOR A BRIDGE ABUTMENT

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Abstract. *The abutment is the part of a bridge that has a more significant dynamic interaction with the soil; the behaviour of the abutment is also influenced by the interaction with the superstructure, producing a reciprocal time-dependent exchange of inertial forces between them. This note illustrates a finite element description of the coupled dynamic interaction of an abutment with the bridge structure and with the soil, occurring in the occasion of a severe seismic event. The computation procedure was entirely implemented in OpenSees with the aim to investigate the dynamic response of the specific abutment of the Pantano viaduct, which would be used as an accessing facility to the still unbuilt Messina Strait suspension bridge, in Italy. The potentiality and versatility of OpenSees were used to reach an accurate numerical modelling of both the soil and the structure. The mechanical behaviour of the soil was reproduced through the Manzari and Dafalias hardening plasticity constitutive model, that was calibrated in order to reproduce the experimental laboratory data. The abutment was regarded as an elastic structure, while the dynamic interaction of the abutment with the superstructure was studied by means of two approaches of increasing complexity and accuracy. Parallel computing, obtained with the OpenSeesSP interpreter, was needed to optimize the computation time for the non-linear time domain analyses. The strategy solution presented herein is useful in that it enhances the current capability to evaluate the dynamic behavior of bridge structures, implementing a coupled soil-structure interaction analysis that considers explicitly the propagation of seismic waves in the foundation soils ant their interaction with the structure.*

1 INTRODUCTION

The Pantano viaduct was designed as the approaching structure to the Messina Strait suspension bridge (Italy) on the Sicilian side of the bridge. As shown in Figure 1, the Pantano viaduct starts at the terminal structure of the suspension bridge and ends on a massive abutment situated on the Messina side. The subsoil is constituted by a thick deposit of Messina gravels, down to a depth of 245 m from the abutment foundation, followed by Continental Deposits extending down to the bedrock, located at a depth of 445 m. The site of the bridge is characterized by a high seismicity due to the presence of several segmentations of active faults. The viaduct is a girder bridge composed of three curved decks, a central railway and two lateral roadways, supported by five piers, by the terminal structure of the suspension bridge and by the abutment. The bridge was designed to transmit most of the longitudinal seismic forces to the abutment that consequently will be loaded by large seismic forces. In the following, the methodology adopted to investigate the dynamic behaviour of the full soil-abutment-superstructure system will be presented, focusing mainly on the modelling technique of the soil-structure interaction models.

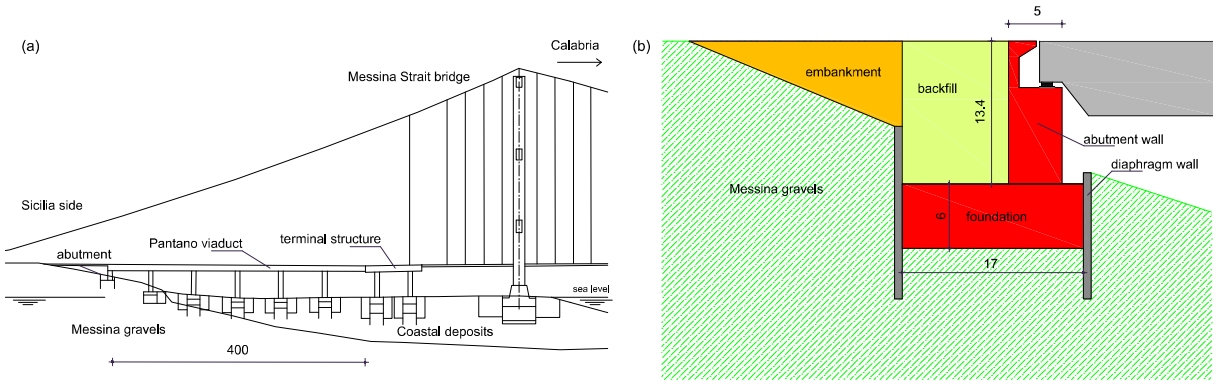

Figure 1: (a) longitudinal section of the Pantano viaduct and of the Messina Strait suspension bridge; (b) geometry of the abutment of the Pantano viaduct.

2 NUMERICAL MODELLING

The system modelling and response computations were performed by using the open source Finite Element analysis framework OpenSees [1] while the mesh of the models was generated and visualized through the pre/postprocessor software GID [2]. The full three-dimensional soil-structure interaction model, depicted in Figure 2, is composed of 400300 elements for a whole extension of 353.5×257.0 m^2 in plan and 128.5 m in depth.

The abutment of the Pantano viaduct, represented in Figure 1, is a massive reinforced concrete structure resting on a foundation slab, that in turn is in contact with the Messina gravels. Because of its large strength compared to the superstructure and the soil, it is reasonable to assume that the abutment exhibits an elastic response under seismic conditions. Hence, every structural member was modelled through the ShellMITC4 element [3] with elastic behaviour, using constitutive parameters relative to a C32/40 strength class concrete in the European standards. A Rayleigh damping was adopted for the elements of the abutment, calibrated in order to consider a damping ratio not greater than 5% for all the significant modes of the abutment.

All the soil domain was discretized through the SSPbrickUP eight node hexahedral elements [4] in which a mixed displacement-pressure formulation is used. The advanced hardening plasticity model developed by Manzari and Dafalias (MD model) [5] was chosen to get an

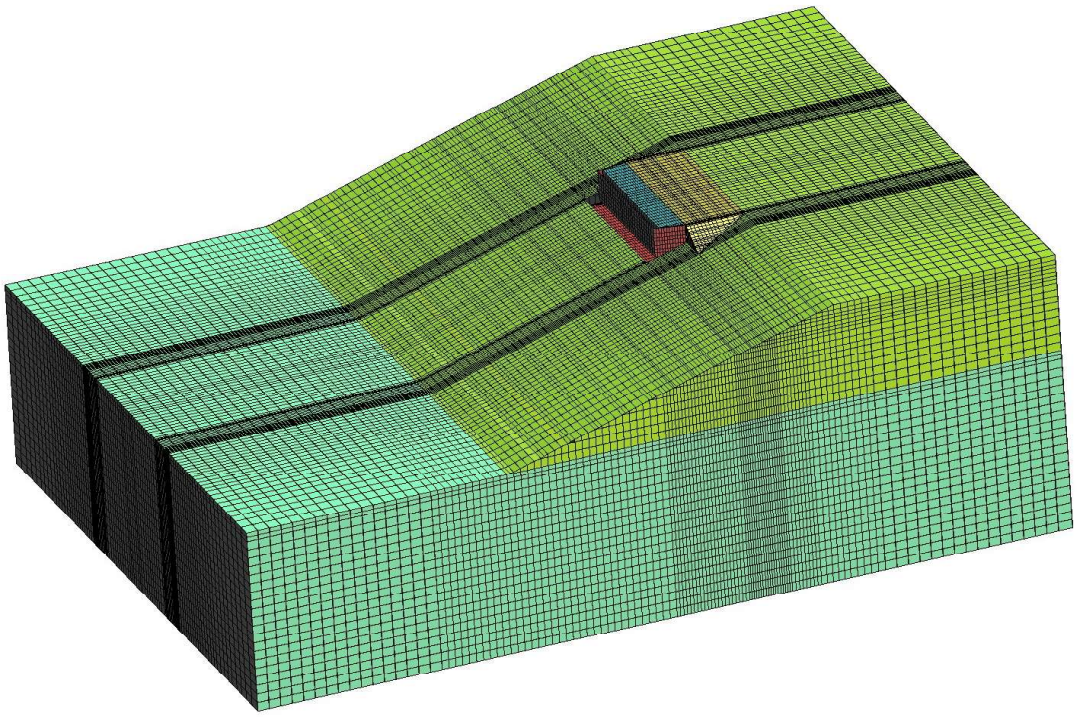

Figure 2: mesh of the three-dimensional soil-structure model

accurate response of the soil under cyclic loading and to predict the development of excess pore water pressures during the earthquake. The parameters of the constitutive model were calibrated against experimental data. It is important to observe that the MD model can reproduce with sufficient accuracy the mechanical behaviour of the soil only in a specific range of strain. More in detail, a calibration based only on monotonic laboratory tests leads to a considerable overestimation of the excess pore water pressure under cyclic conditions and, as a result, an inaccurate prediction of the mechanical response in undrained conditions. To overcome this issue, the calibration was aimed to obtain a good match with the experimental trends under cyclic conditions and, at the same time, to have a reasonable static response in the range of strain of interest for the problem under examination. The MD model is able to reproduce the effective energy dissipation as a function of the strain level, however an additional small damping ratio was introduced using the Rayleigh formulation only to attenuate the effects of spurious high frequencies.

Behind the wall of the abutment two zones can be distinguished: the backfill and the embankment. The former is the part directly in contact with the abutment and is made of a soil-cement mix to have a large stiffness and to avoid the development of significant plastic strains. Therefore the backfill was modelled as an elastic-perfectly plastic material, with a Young's modulus of 10^6 kPa that respects technical provisions on the stiffness, a Poisson's ratio of 0.2, an angle of shearing resistance of 38° and a cohesion equal to 200 kPa. Moreover, the Rayleigh damping model was associated with the elements of the backfill calibrated on the frequency content of the seismic input. Conversely, the embankment is a partially saturated soil, with the presence of negative pore water pressure (suction) providing non-zero stiffness and strength at small stress levels. The mix design for the soil of the embankment was chosen to have a stiffness and a degree of compaction greater than the correspondent limit values imposed by technical provisions. The MD model was adopted to simulate the behaviour of the embankment with an appropriate calibration of the parameters, in which the effect of the suction was modelled as a modest increment of the material stiffness. As done for the soil do-

main, a small Rayleigh damping was added to these elements to stabilized the dynamic time stepping.
The bridge has three curved decks, two lateral roadways designed as continuous steel box girder beams and a central railway composed of a mixed steel-concrete beam for each span, that are supported by five piers with a reinforced concrete box section. All the decks are connected to the abutment by a series of bearings that impede the relative displacements with the abutment. The dynamic interaction between the abutment and the bridge structure was initially modelled by applying equivalent static forces at the top of the abutment. At a successive stage, a more rigorous method was introduced, conceived to reproduce the frequency-dependent transmission of the dynamic interaction forces between the abutment and the superstructure through a transfer tensor, which represents the global effects of the multi-directional dynamic response of the superstructure.
A staged analysis procedure was adopted with gravity loads applied first and followed by the dynamic simulation, in which the use of the parallel computing was needed to get reasonable computation times. During the seismic excitation, the Lysmer and Kuhlemeyer absorbing boundaries [6] were applied along the lateral boundaries of the model, implementing an automatic procedure to set the dashpots with their properties, while the seismic input, applied at the base of the model, resulted from a deconvolution analysis in order to limit the vertical extension of the numerical model. In this way, the seismic actions reaching the abutment derive from the combined effect of the propagation of the seismic waves through the soil and the dynamic interaction of the soil with the structure.

3 CONCLUSIONS AND PERSPECTIVES

The numerical procedure exposed herein is part of an ongoing research on the dynamic response of bridge abutments, starting from the case study of the Pantano viaduct. The purpose of this research is to define useful tools and methods for dealing with the complex soil-abutment-superstructure interaction and to explore the dissipative capabilities deriving from the interaction between the soil and the abutment.

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