Dynamic testing of marine sediments at the Pelješac bridge site

Essais dynamiques des sédiments marins sur le site du pont de Pelješac

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ABSTRACT

The complex geotechnical investigations were performed at the location of the long bridge at the south Adriatic. The sea depth at the location is 27 to 28m. Marine sediments, deposited in horizontal layers, are very soft to soft high plasticity clay with silt, from the sea bottom to the depth of 60m where overconsolidated clay with fragments of lime and shells was found. The depth of base lime rock varies along the bridge from the surface at the coasts to 100m under the sea bottom. Seismicity of the location is significant. Comprehensive dynamic testing was performed in order to establish the representative seismic soil profile. Vane shear, SCPT and CPTU testing (seismic cone penetrometer and piezocone) were performed to the depth of 25m, as well as down hole testing to the depth of 80m. Numerous classification tests, compressibility and strength tests were performed in the laboratory. Undisturbed specimens from the borehole for down hole measurements were tested in the resonant column apparatus, double specimen direct simple shear device (DSDSS), and in the triaxial apparatus with bender elements. Effects of mean effective stress and excitation characteristics are investigated in all tests. The compilation of basic investigation results is presented. Values of shear modulus obtained from all the laboratory tests and from wave velocity measurements are compared taking into account shear deformation which varies from 0,00003% in resonant column tests to 3%, showing very good agreement.

RÉSUMÉ

Des investigations géotechniques complexes ont été réalisées sur le site du pont Pelješac au sud de la mer Adriatique, où la profondeur de la mer est 27 à 28m. Les sédiments marins, déposés dans les couches horizontales, sont des argiles très plastiques, très molles à molles, jusqu'à la profondeur de 60 m tandis qu'au dessous les sédiments sont composés de limons argileux ou d'argiles surconsolidées. Le long du pont, le lit rocheux s'enfonce depuis la surface jusqu'à une profondeur de 100m. La sismicité du site est considérable avec 7 tremblements de terre de magnitude supérieure à 6 enregistrées au cours du siècle passé. On a réalisé un vaste programme d'essais en laboratoire pour établir les caractéristiques à utiliser dans les analyses des effets sismiques locaux: essais standard de classification, compressibilité et résistance au cisaillement. Les essais de scissomètre, cône sismique et piézocône ont été effectué jusqu'à une profondeur de 25m, et les vitesses de propagation ont été mesurées par sismique axiale dans les sondages réalises à 80m. Des échantillons non remaniés obtenus de même trou de forage ont été testés à la colonne de résonnance, dans l'appareil de cisaillement direct simple à deux échantillons (DSDSS), et dans l'appareil triaxial instrumenté avec des languettes piézocéramiques. Les effets de contrainte effective moyenne et les caractéristiques d'excitation ont été analysés. Les valeurs de module de cisaillement obtenues dans tous les essaies ont été comparées pour les déformations entre 0,00003% et 3% et une bonne correspondance à été obtenue.

Keywords: geotechnical investigation, marine sediments, dynamic soil testing

1 INTRODUCTION

The long bridge at south Adriatic is designed to connect the Croatian mainland to the Pelješac peninsula. The length of the beam and cable-stayed bridge is to be 2340m, with main span of 568 m and clearance of 55m above sea level. The sea depth at the location is 27 to 28m. The bridge is situated in the area of high seismicity.

The complex geotechnical investigations were performed at the bridge site in order to obtain relevant geotechnical data for the foundation design as well as to establish the representative seismic soil profile for the site response analyses.

Geomorphology was investigated previously from the sea bottom using single beam echosounder and side scan sonar and in that campaign also the geophysical survey by a sub-bottom profiler has been performed along two lines parallel to the bridge alignment.

The offshore investigations have been performed from a specialized geotechnical vessel fully equipped for drilling, sampling and in-situ testing. The investigations included continuous shear wave velocities survey which was conducted to the depth of 40 m under the sea bottom along two profiles parallel to the bridge axis and in three orthogonal crosslines. In situ testing, as well as drilling several boreholes with soil sampling, was performed from the ship. Vane shear, SCPT and CPTU testing (seismic cone penetrometer and piezocone) were performed to the depth of 25m, as well as down hole testing to the depth of 80m.

Laboratory tests have been performed both on the vessel and in the laboratories onshore. They included numerous classification tests, compressibility and strength tests as well as special testing on undisturbed samples.

The results of the geotechnical investigations and their interpretation are presented in reports prepared by D'Appolonia (2005) and IGH (2007).

2 SITE GEOLOGY

The wider area of the bridge site is the Dalmatian region, which is part of the Dinarides geologic domain. The chain formed by the overthrusting of the eastern units on the Adriatic microplate to the west. The mountains of the Dinarides mountain chain stretch in NW-SE direction, parallel to the coast.

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From the previous geologic studies the geological formations encountered on land are limestone and rare flysh, dated Paleogene; limestone, dated Upper Cretaceous; dolostone and limestone, dated Upper Triassic. Recent sediments are present in the nearshore zone and in the Neretva River plain.

The region is of high seismicity and a large number of earthquakes have occurred. In the range of 100 km from the bridge site, 7 earthquakes of magnitude over 6 occurred in the last century.

Geophysical and geotechnical investigations at the bridge site have demonstrated that the basic rock is 40-100m below the actual sea bottom, and the soil profile from the base rock to the sea bottom level consist dominantly of clay sediments, mostly horizontally layered.

The results of many geological investigation in west Adriatic coast and north Adriatic and speleological, even archaeological evidences, undoubtedly demonstrate the intensive transgression of Adriatic Sea in last 18000-20000 years (e.g. Benac et al. 2004; Surić et al. 2005; Ridente and Trincardi 2002, Trincardi et al. 2004; Ravaioli et al. 2003; Capotondi et al. 1999; De Lazzari 2004; Forenbaher 2002). According to these estimates the sea level has raised 100-120m during this period.

Therefore, the majority of the registered deposits in the soil profile have been recently sedimented in marine environment. The origin of the material is mostly deposits supplied from the near Neretva River. The upper clay layers have large calcium content, grey to olive-grey colour and relatively low mechanical characteristics.

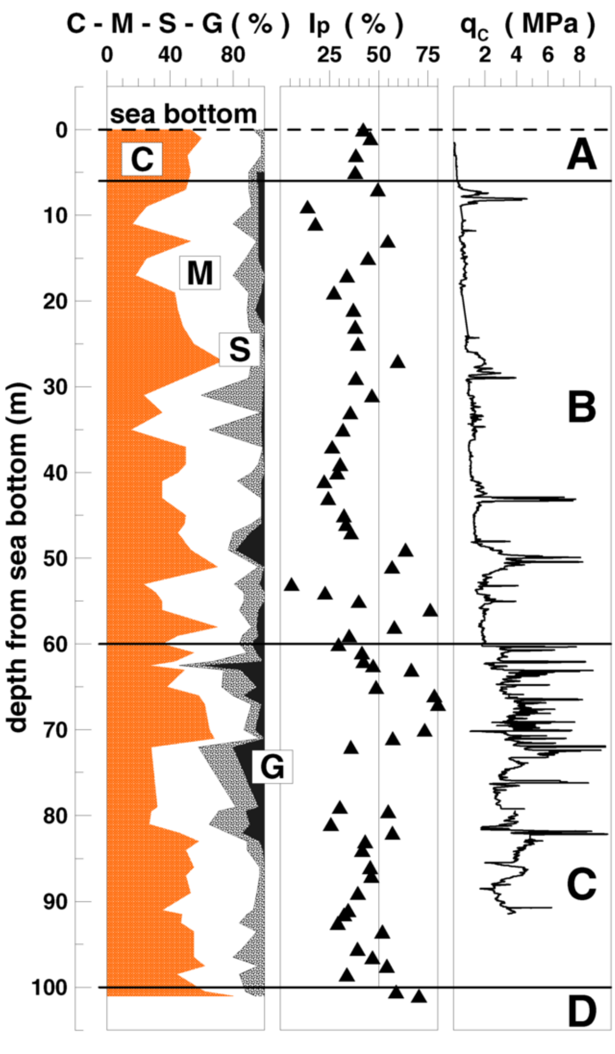

Figure 1. Typical profile of marine sediments at Pelješac bridge site.

The clay deposits in depths greater then 60m from the sea bottom are significantly different, showing less calcium, more quartz content, brown to yellow-brown colour, greater strength and lower compressibility than the upper layers.

Based on the geotechnical investigations, the soil deposits can be grouped in four units (depths from the sea bottom):

- Unit A: 0.0 to 6.0 m, constituted of very soft to soft high plasticity clay;
- Unit B: 6.0 to 60.0 m, composed of a sequence of medium stiff to stiff high plasticity clays and silts. This unit was subdivided in several subunits of common properties;
- Unit C: 60.0 m to the bedrock, comprising very stiff to hard clays, locally cemented. In this unit also 2 subunits can be identified;
- Unit D: bedrock, constituted of limestones, with a variable degree of weathering and fracturing.

The typical soil profile is presented in Figure 1 by distribution of granulometric content and plasticity index along the depth, as well as by typical CPT cone resistance variation where marked difference in the layers under 60m (unit C) are obvious. In this figure also the main soil units are shown.

3 DYNAMIC TESTING

Seismic profile of the site deposits is presented by distribution of shear wave velocities along the depth. Several techniques were used:

- continuous shear wave survey, using spectral analysis of surface waves, to the depths of 40m from the seabed,
- direct shear wave velocity measurement with seismic cone to the depths of 25 m,
- downhole measurements in one borehole to the depth of 80m.

The range of data from continuous survey, as well as the mean down-hole results is summarized in Figure 2. The general agreement of results is achieved.

In this figure the selected (design) values for site response are also presented. The design seismic profile is mainly based on down-hole results and the values under 80m are assumed.

Dynamic laboratory tests were performed on undisturbed soil samples and included the following tests:

- resonant column test (RC) from samples at several depths,
- double specimen direct shear test (DSDSS),
- triaxial tests with bender elements (BE).

The dynamic tests were performed in order to obtain the curves of shear modulus reduction and damping vs. cyclic shear strain (RC and DSDSS) and effects of mean effective stress on dynamic shear modulus at small strains (all tests).

The results of variation of maximal shear modulus with effective stress for all tests are presented in Figure 3. In the RC tests and tests with bender elements (BE), the effective pressure varied for particular sample. The DSDSS tests were performed at the stresses approximate to the in situ stress of the tested specimen.

It is shown that general agreement between the tests at samples of comparable depths is very good. The trends of results for resonant column and tests with bender elements are consistent, while the results of DSDSS show some deviation at lower pressures.

The regression analysis was performed for each individual test to obtain the parameters for presentation of maximal shear modulus, Gmax , in the form of Eq. 1:

$$G_{max} = A\, \sigma'^{n} \qquad (1)$$

where σ’ is effective stress, A and exponent n are obtained by linear regression. The results are summarized in Table 1.

The exponent n is approximately 0.5 for most tests as suggested in literature.

Table 1. The linear regression results for Eq.1

Test number (depth in m)	A (kPa)	n	R^2
RC 13	1702	0.5986	0.992
RC 23	3537	0.5094	0.987
RC 35	3537	0.5094	0.987
RC 45	4867	0.5644	0.997
RC 58	2725	0.5845	0.989
Bender 43m	10721	0.4569	0.995

The results in table also enabled the calculation of shear wave velocity for tests at particular depths and corresponding effective stresses. These results were returned to Figure 2 and compared to other in situ tests. It is shown that the values obtained in the laboratory are somewhat lower than the values measured in situ.

The results of tests with varying cyclic shear strain are summarized in Figure 4 (modulus reduction) and Figure 5 (damping ratio). The range of shear strains covered by both (RC and DSDSS) tests is from 0,00003% to 3%, where DSDSS test revealed the results for larger shear strains than RC test.

Although the scatter of the results seems large it should be taken into account that the results for individual tests are shown together without any particular differentiation regarding other soil properties. The comparison with appropriate literature recommendations (Vucetic & Dobry 1991) shows good agreement. The comparison with average soil curves from older literature demonstrates significant difference, thus justifying the performed tests.

The curves used in site the response analyses for all clay layers correspond to mean value of results and lower values of recommended curves.

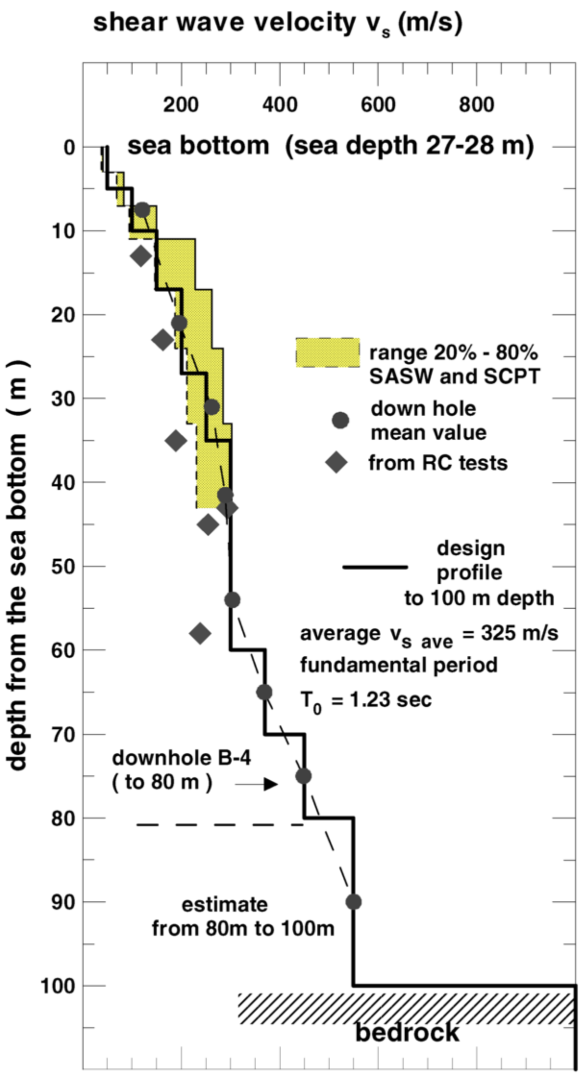

Figure 2. The offshore seismic profile at bridge site.

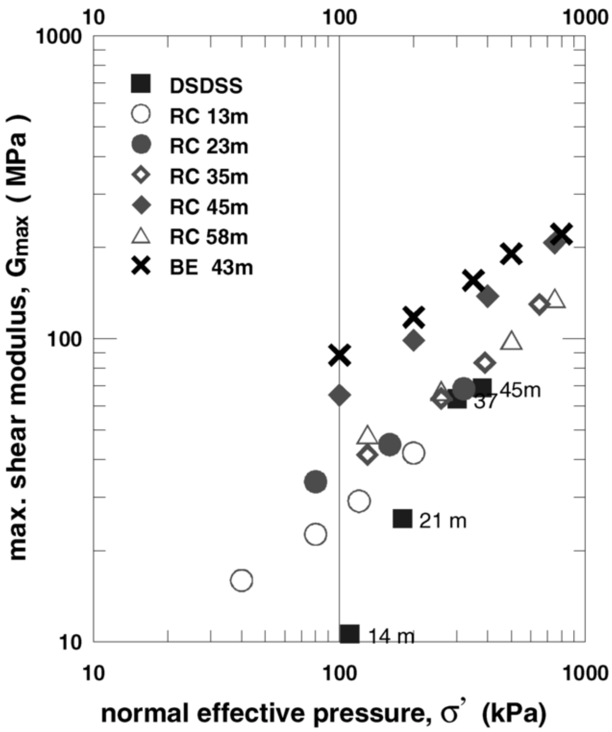

Figure 3. The effect of effective pressure on dynamic shear modulus.

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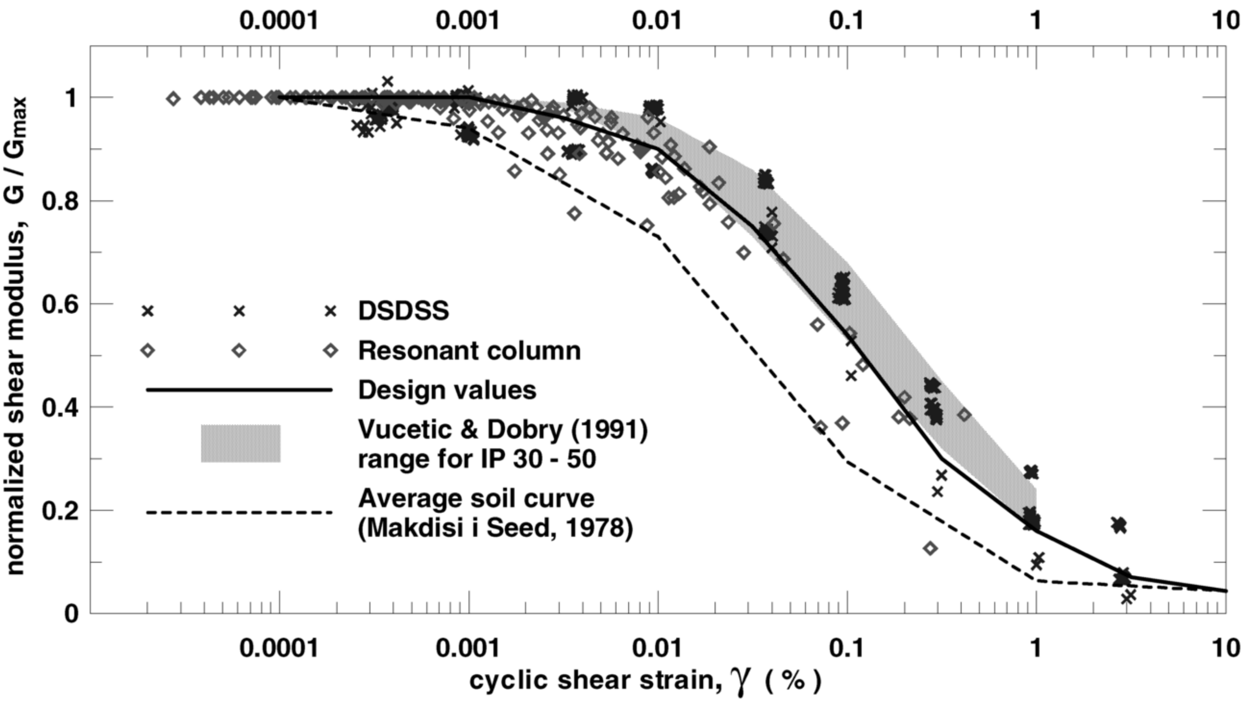

Figure 4. The reduction of shear moduli with cyclic shear strain.

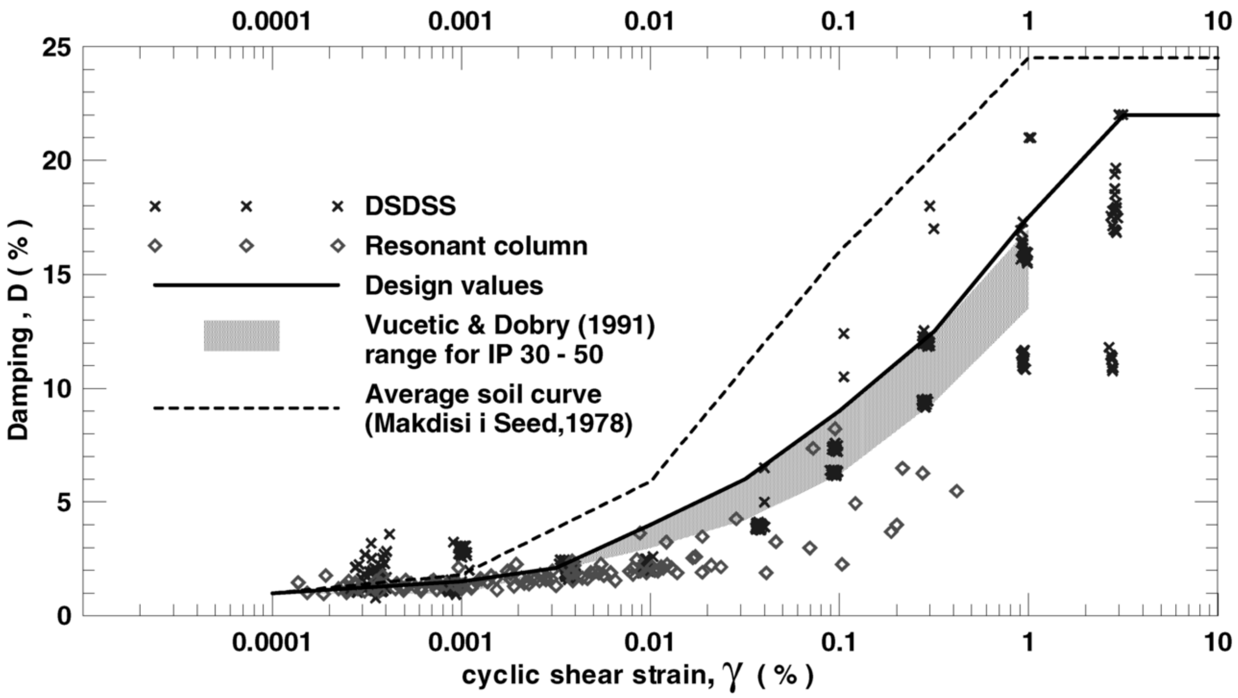

Figure 5. Damping ratio versus cyclic shear strain.