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The Influence of Soil Characteristics in Seismic Response of Embedded Structures

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Abstract: The seismic response of a large wastewater collector box-type is performed by spectral analysis and direct time integration methods. The influence of mechanical characteristics of surrounding soil on structure seismic response is investigated. For this purpose the soil bulk modulus was successively considered 40,000 kPa and 80,000 kPa. The study points out the kinematic interaction soil-buried structure is usually more important than inertial interaction. Over wastewater collector is placed a river channel with 2.30 m deep water. The analysis shown the water from river channel led to significant increase in structure sectional stresses during seismic action.

Key words: Embedded structures, seismic response, parametric study.

1. Introduction

Dambovitza river crosses Bucharest city, the capital of Romania from north-west to south-east. The river is the main collector of rainwater and groundwater from city area. Over the centuries in the river was also discharged wastewater from the city sewerage system. Therefore while the river became increasingly polluted and no longer met environmental requirements [1].

Between 1984-1988 on Dambovitza river in Bucharest area along of 10 km were carried out extensive rehabilitation works. The river bed was deepened in order to carry out the main collector channel as reinforced concrete structure of compartmented box—type for the city's wastewater. Above of box-type structure, separated by a common floor, the river was channeled and fragmented in a cascade consisting of seven small reservoirs created by river dams. In order to control the flow along cascade on Dambovitza river, upstream of Bucharest city was carried out an important artificial reservoir named Lacul Morii with volume of 20 million m^3 for flood control and multy-years regulation of the river flow. In Fig. 1 is presented a typical cross section of the Dambovitza development in Bucharest, Ciurel—Opera sector, about 2 km downstream of Lacul Morii reservoir.

Bucharest city is located in an area of highest seismicity generated by well known Vrancea hypocenter. The statistics shown that Vrancea hypocenter generates two-three destructive strong subcrustal earthquakes per century. The last Vrancea destructive earthquake with 7.4 magnitude was at 4th March 1977 provoking 1,530 human victims and 11,300 wounded from which 90% were in Bucharest and very important material losses (about 2 billion US$). Fig. 2 illustrates two accelerograms of Bucharest—Vrancea 4th March 1977 earthquake recorded in subsoil of a building from the city [2].

In the conditions mentioned before, the seismic safety of the main collector for wastewater needed a special attention in design and operation. The seismic safety of buried (embedded) structures is essentially influenced by the dynamic behavior of the surrounding deposit. In the present case, taking into account, the collector conveys continuously the wastewater and over it exists the artificial channel bed of Dambovitza river, the seismic interaction water—structure is also important for seismic response of the structure [3-7].

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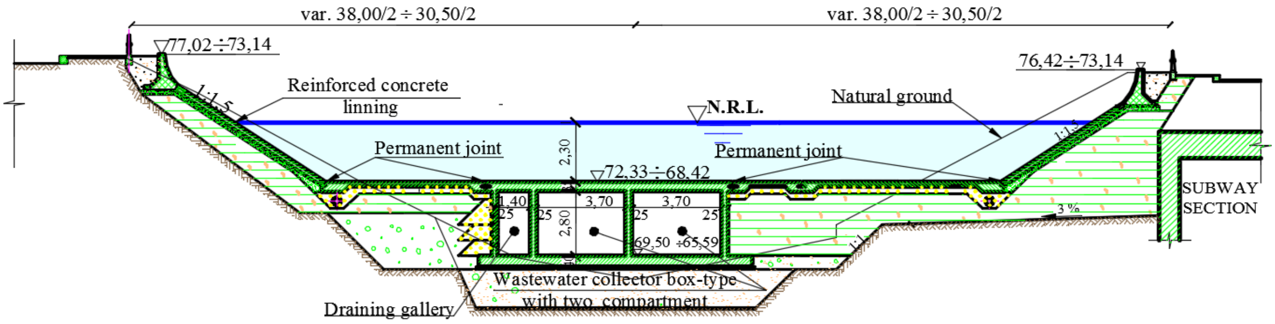


Fig. 1 Cross section through Dambovitza river development in Bucharest city, Opera—Ciurel sector.

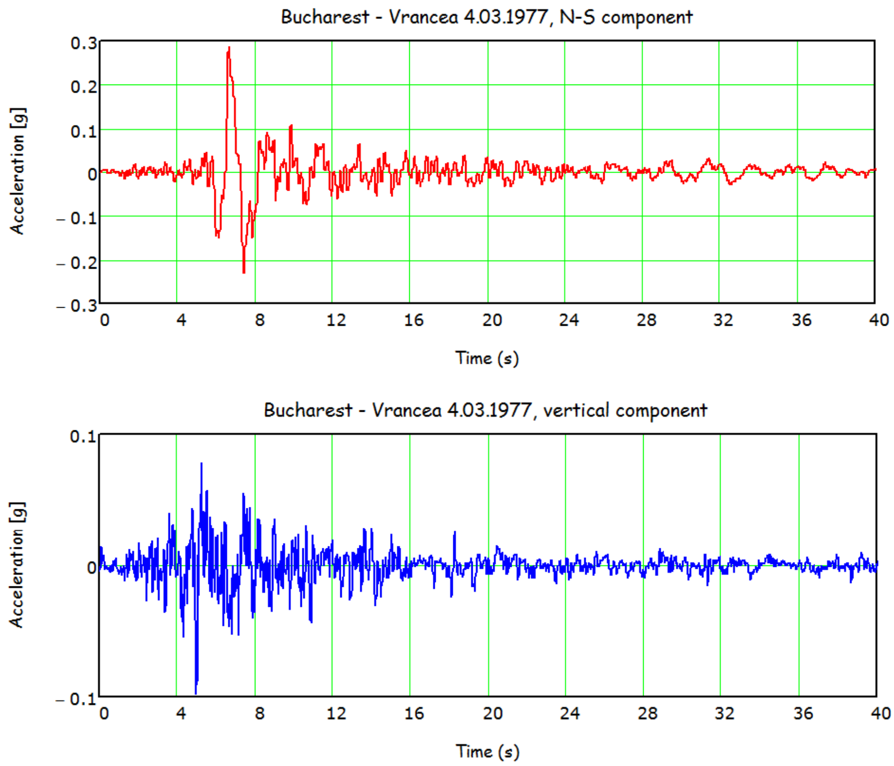


Fig. 2 Accelerograms Bucharest–Vrancea 4.03.1977 earthquake recorded in a building subsoil from Bucharest city: N-S component and vertical component.

The potential errors introduced by ignoring the interaction effects of structure with surrounding soil and water can certainly not be overlooked.

As the structure is relatively stiff compared with adjacent soil, the ground motions are constrained. This phenomenon called “kinematic interaction” depends on the geometrical and stiffness configuration of the structure, soil characteristics and variation of the seismic waves. Usually the kinematic interaction effect on the seismic response is dominant in comparison with the influence of inertial soil—structure interaction. The parameters of interest in soil—structure interaction analysis are strains and stresses, not acceleration of the soil.

Direct solutions of complete soil-fluid-structure interaction approach can be obtained by FEM (finite element method). This technique is applied in the present paper.

The laboratory and in site tests results concerning soil characteristics have shown big scattering. In order to evaluate the influence of the soil characteristics on seismic response of the embedded structure, the analyses were performed for two hypotheses concerning soil characteristics: pessimistic and respectively, optimistic one. They were the envelopes of test results.

The hydrodynamic effects of water contained in collector and from river channel, generated by earthquake were considered using added mass procedure based on Westergaard relation and acoustic finite elements based on Helmholtz bi-dimensional differential equation.

The accelerograms from Fig. 2 of the Bucharest-Vrancea 04.03.1977 earthquake were applied at the boundaries of the finite element mesh, successively on horizontal direction and horizontal + vertical directions.

The seismic analyses were performed taking into account the linear elastic behavior of materials using Abaqus software. The structure response was computed by spectral analysis method and direct time integration method, the results being compared and commented [8].

The sectional stresses acting on collector structure in spectral analysis were evaluated in compliance with RSS (Root Sum Square) relation of the stresses in representative mode shapes.

Finally is pointed out the seismic vulnerability of the structure analyzed including the influence of the surrounding soil. Generally, the results can be extended to other embedded (buried) structures.

2. Mathematical Model and Input Data

Fig. 3 illustrates finite element mesh of the foundation-water-structure unitary system in compliance with Abaqus software. The extension of the foundation was chosen in order to avoid the influence of boundary conditions on seismic response of the structure.

The structure (collector) was modeled with beam elements (B22-A3 node quadratic beam in a plane). The foundation was discretized with quadrilateral plane strain elements (CPS4: A4 node bilinear plane stress quadrilateral). The water from collector and Dambovitza channel was discretized with quadratic elements 2-D acoustic (AC2D8: A8 node quadratic 2-D acoustic quadrilateral). The analysis was performed for 1 m along Dambovitza river development.

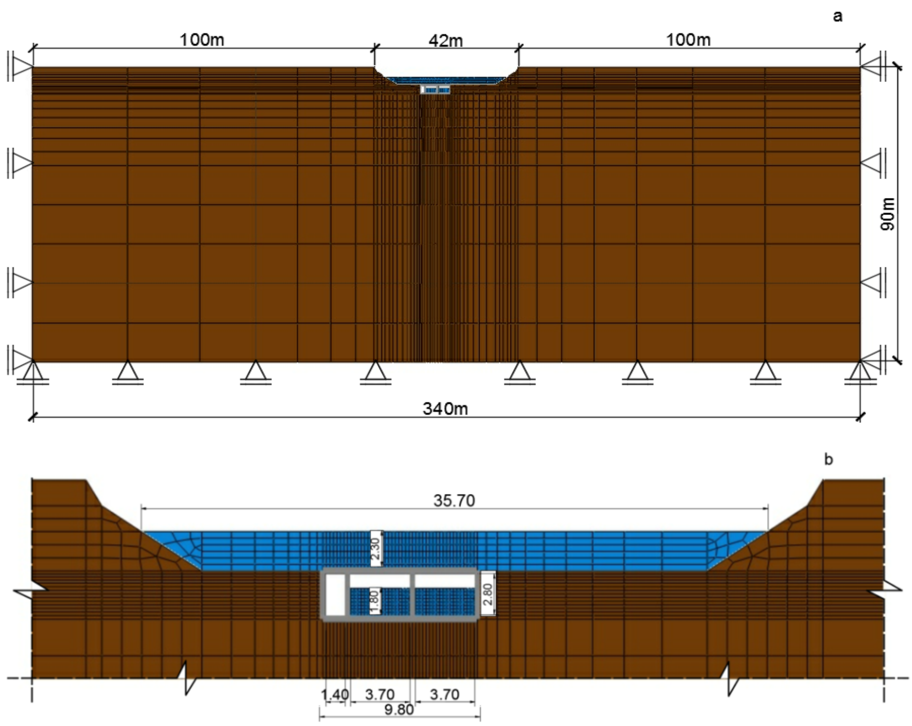


Fig. 3 Finite element mesh of the foundation-water-structure unitary system: a-general, b-detail.

The boundary conditions were applied at the limits of the mesh, as follows: at the bottom, translations on y direction (vertically) were blocked, excepting corner nodes were the both translations on x and y directions were blocked and at the both lateral limits, the translations on x direction (horizontally) were blocked.

In Table 1 is shown some data about finite element mesh, respectively the number of the nodes and elements for each subsystem.

The properties of materials from the system are presented in Table 2. It may be remarked that for foundation soil two characteristics, pessimistic and optimistic were successively considered.

In order to perform spectral analysis, design spectra were necessary to be evaluated from the accelerograms presented in the Fig. 2. They were computed using well-known relation with convolution integral. Design spectra were obtained by smoothing the values from response spectra according to the rules of the least squares. Design spectra for both accelerograms and fraction of the critical damping $v = 0.05$ are presented in Fig. 4.

Damping matrix $[C]$ used in direct time integration method was evaluated according to linear Rayleigh relation, the coefficients α and β being computed based on two mode shapes of the system having the longest natural periods:

$[C] = \alpha\,[M] + \beta\,[K]$

$\alpha = 2\,v\,\omega_1\,\omega_2/(\omega_1 + \omega_2)$ and $\beta = 2\,v/(\omega_1 + \omega_2)$

where, $[M]$ and $[K]$ are mass matrix and stiffness matrix;

$v = 0.05$ fraction of critical damping;

$\omega_1\ \omega_2$ two shortest circular frequencies of the system (rad/s);

The α and β values calculated in different hypotheses are presented in Table 3.

For both pessimistic 40 MPa and optimistic 80 MPa characteristics of the foundation soil, the load combinations considered in seismic response of the Bucharest main collector for wastewater are presented in Table 4.

3. Some Results Concerning Seismic Analysis of the Embedded Structure

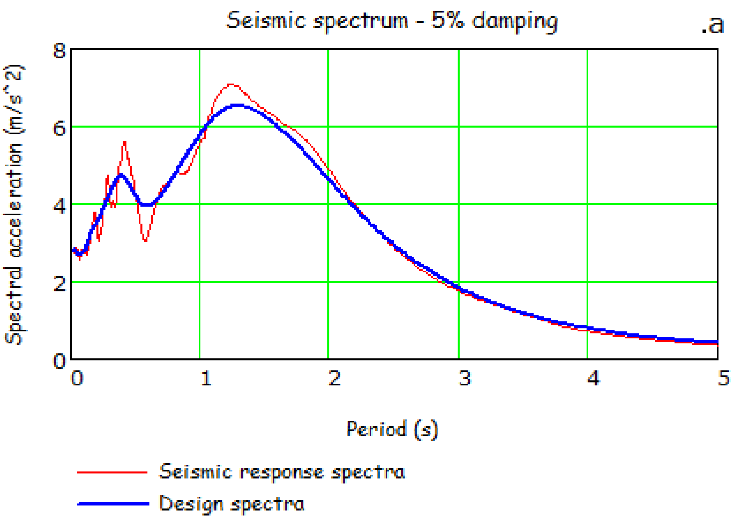
The values of first six longest natural periods of the foundation-water-structure unitary system in different hypotheses are illustrated in Fig. 5. It may be remarked the significant influence of the soil characteristics on the natural periods of the system. For instance the fundamental period increased with about 40% for a decrease of the soil bulk modulus from 80 MPa to 40 MPa.

Table 1 Data on finite element mesh.

Nodes/Elements Sub-systems	Nodes	Elements
Collector	290	146
Foundation	1,944	1,810
Water in collector	1,332	399
Water in river channel	1,140	342
Total	4,706	2,697

Table 2 Material characteristics.

Properties	Reinforced concrete	Foundation soil	Water
Mass density (kg/m^3)	2,400	0	1,000
Static Poisson coefficient	0.18	0.30	
Dynamic Poisson coefficient	0.23	0.30	
Static Young modulus (MPa)	23,000	40/80	
Dynamic Young modulus (MPa)	27,600	40/80	
Bulk modulus (MPa)			2,200



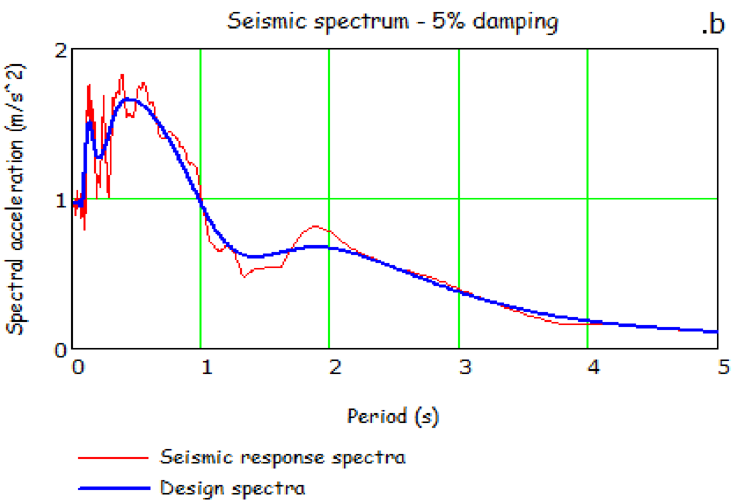


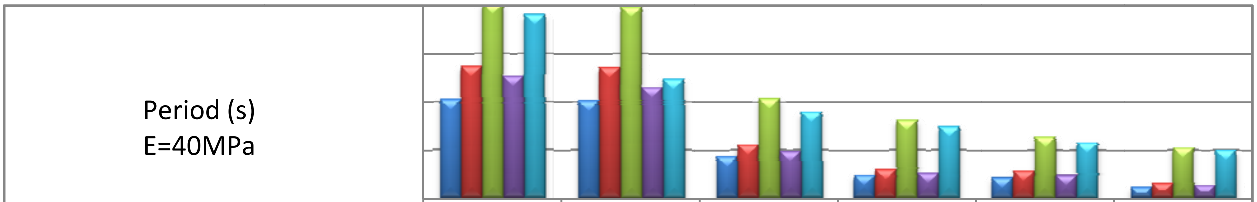
Fig. 4 Design spectra (blue color) and seismic response spectra (red color) for 5% damping rate on horizontal (a) and vertical (b) directions.

Table 3 The α and β parameters in Rayleigh relation.

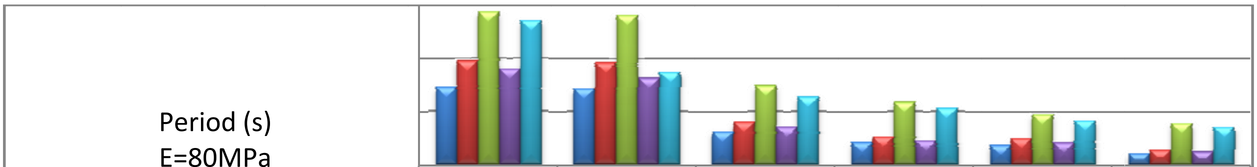
Young modulus of the foundation soil (kPa)	Added mass		Acoustic elements	
	α	β	α	β
40,000	0.78322	0.00319	0.99882	0.00239
80,000	1.10372	0.00226	1,40965	0.00169

Table 4 The load combinations taken into account in seismic analyses.

Hypothesis number	E_f = 40,000 kPa/E_f = 80,000 kPa						
	Static analysis			Dynamic analysis			
	Dead weight	Hydr. prs. in collector	Hydr. prs. in channel	Acoustic elements: Water in collector	Acoustic elements: Water in channel	Horizontal earthquake	Vertical earthquake
1	Yes	Yes	-	Yes	-	Yes	-
2	Yes	Yes	Yes	Yes	Yes	Yes	-
3	Yes	Yes	-	Yes	-	Yes	Yes
4	Yes	Yes	Yes	Yes	Yes	Yes	Yes



	1	2	3	4	5	6
Without water	0.205	0.202	0.086	0.047	0.043	0.022
Water in collector - Westergaard	0.274	0.272	0.111	0.059	0.058	0.030
Water in collector and channel- Westergaard	0.404	0.398	0.208	0.163	0.129	0.106
Water in collector - Acoustic	0.253	0.230	0.097	0.052	0.048	0.026
Water in collector and channel - Acoustic	0.382	0.247	0.180	0.149	0.117	0.100



	1	2	3	4	5	6
Without water	0.146	0.144	0.062	0.043	0.038	0.022
Water in collector - Westergaard	0.195	0.193	0.081	0.053	0.051	0.029
Water in collector and channel- Westergaard	0.287	0.282	0.149	0.118	0.096	0.080
Water in collector - Acoustic	0.180	0.163	0.072	0.046	0.042	0.025
Water in collector and channel- Acoustic	0.271	0.175	0.128	0.107	0.085	0.073

Fig. 5 The largest natural periods (s) of the system evaluated in different hypotheses.

The influence of the interaction with water may be also remarked. The fundamental period increased with about 90% when water exists both in collector and river channel compared to the case when they are empty. The periods evaluated by added mass approach versus equivalents evaluated with acoustic elements are longer suggesting the forces acting on structure in first case are comparatively higher. This means the added mass approach is conservative one.

Taking into account the results from free vibration analysis, the seismic response of the collector was evaluated by spectral analysis and by direct time integration method using added mass approach for interaction with water.

Father, the following notations are used for different loads acting on collector structure: G—dead load, PHC—hydrostatic pressure in collector, PHR—hydrostatic pressure in river channel, G + PFC = S, G + PHC + PHR = TS, DSH—design spectrum (Fig. 4a) of the horizontal accelerogram applied on horizontal direction, DSV—design spectrum (Fig. 4b) of the vertical accelerogram applied on vertical direction, EH—North-South accelerogram ($a_{\max}$ = 0.19 g) (Fig. 2a) applied on horizontal direction, EV—vertical accelerogram ($a_{\max}$ = 0.13 g) (Fig. 2b) applied on vertical direction.

Fig. 6 and 7 represent diagrams of bending moments (*M*) and axial forces (*N*) acting on collector structure due to load combination G + PHC + PHR ± DSH ± DSV. The structure response was evaluated by spectral analysis for E_f = 40,000 kPa and respectively, E_f = 80,000 kPa. A more comprehensive analysis of the sectional stresses (*M*, *N*) values in representative points of the collector structure in different load combinations can be made based on the data in Table 5.

In Fig. 8 are illustrated in few representative points

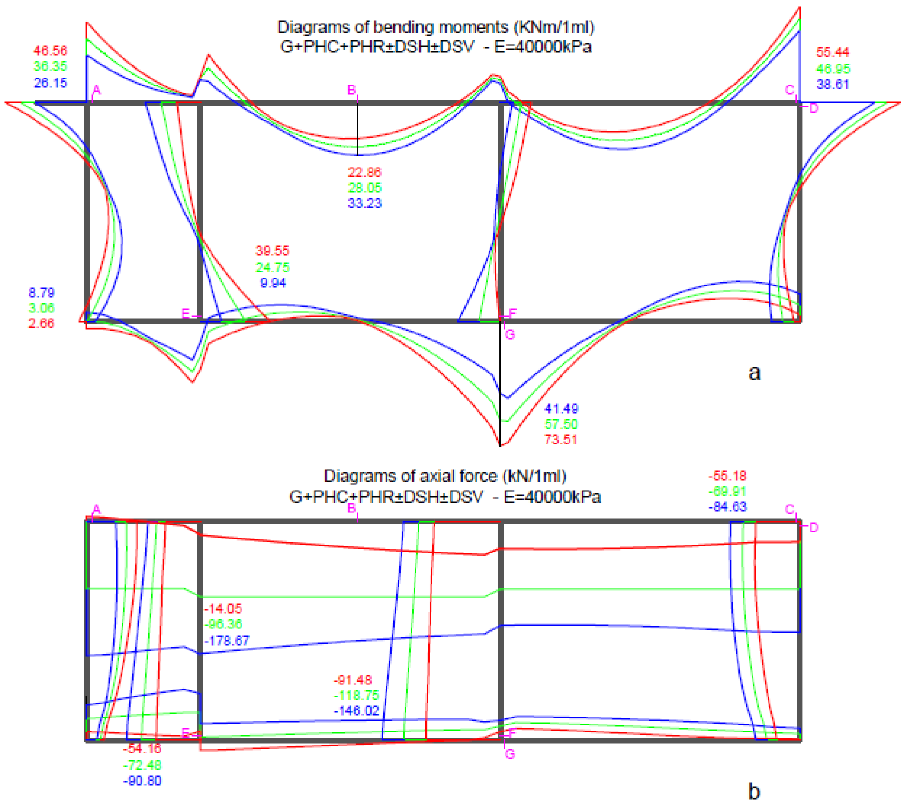


Fig. 6 Diagrams of bending moments (kNm/1 ml) and axial forces (kN/1 ml) of the load combination G + PHC + PHR ± DSH ± DSV resulted in spectral analysis for E_f = 40,000 kPa.

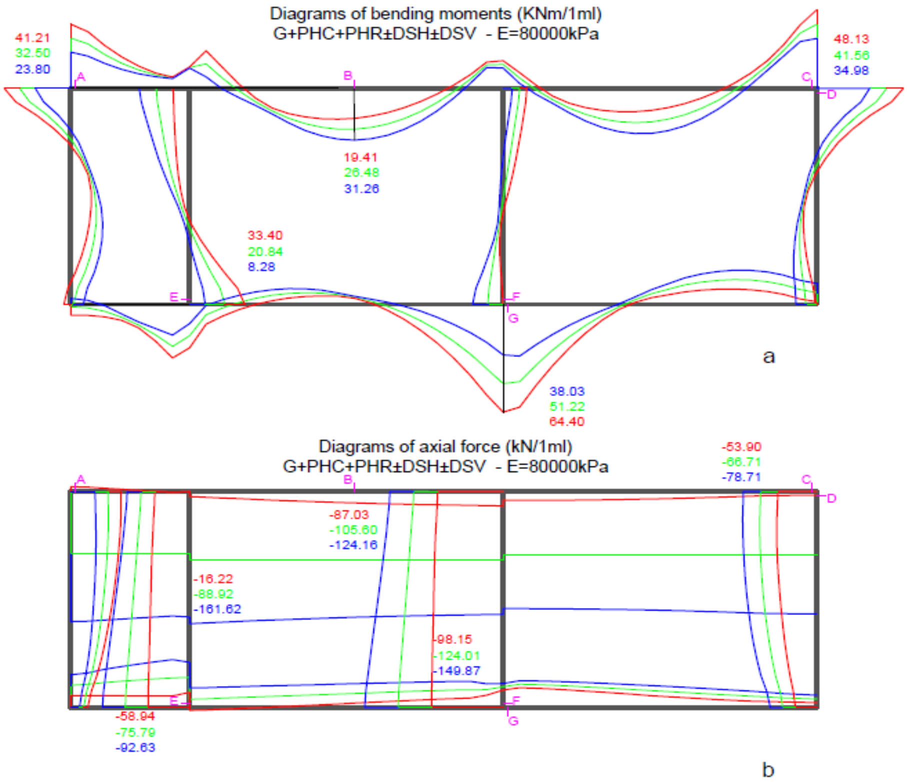


Fig. 7 Diagrams of bending moments (kNm/1 ml) and axial forces (kN/1 ml) of the load combination G + PHC + PHR ± DSH ± DSV resulted in spectral analysis for E_f = 80,000 kPa.

Table 5 Maximum values for M and N in different hypotheses.

Point (see Fig. 6a)	E_f = 40,000 kPa		E_f = 80,000 kPa	
	G + PHC + PHR ± DSH			
	Max. M (kNm/ml)	Max. N (kN/ml)	Max. M (kNm/ml)	Max. N (kN/ml)
A	32.55	-85.84	27.23	-77.90
B	14.55	-82.44	12.85	-71.10
C	40.28	-102.96	32.18	-88.99
D	40.28	-32.97	32.18	-28.11
E	32.03	-19.03	25.03	-21.06
F	21.88	-34.44	15.36	-39.18
G	37.21	14.70	29.94	8.18
Point (see Fig. 6a)	E_f = 40,000 kPa		E_f = 80,000 kPa	
	G + PHC + PHR ± DSH ± DSV			
	Max. M (kNm/ml)	Max. N (kN/ml)	Max. M (kNm/ml)	Max. N (kN/ml)
A	46.56	-183.16	41.21	-169.10
B	33.23	-160.00	31.26	-143.85
C	55.44	-149.92	48.13	-137.24
D	55.44	-84.63	48.13	-78.71
E	39.55	-90.80	33.40	-92.63
F	25.30	-146.02	20.47	-149.87
G	73.51	-25.28	64.40	-31.46

Note: M are represented on the tension side of the face; N (+) is tension.

(see Fig. 6a) the oscillograms of the bending moments and axial forces computed by direct time integration method during Bucharest-Vrancea NS and V 4.03.1977 earthquake and compared with the equivalent results in spectral analysis.

In compliance with Romania regulation based on Eurocode2 for calculus of the reinforced concrete section (ASRO 2004b, SREN 1992-1-1: 2004 Eurocode2) were evaluated the resistant capacity (resilience) of the collector structure components (floor, walls, apron). The results are the followings:

Floor: $M_{capable}$ = 103.3 kNm/1 ml

Apron: $M_{capable}$ = 151.9 kNm/1 ml

Wall: $N_{capable}$ = 156.0 kN/1 ml

Wall: $M_{capable}$ = 54.0 kNm/1 ml

In the hypothesis E_f = 40,000 kPa, the collector structure has comparatively higher displacements and strains than for hypothesis E_f = 80,000 kPa. In other words, a more important quota of the earthquake energy is taken out by a terrain with superior mechanical characteristics and so the embedded structure is better protected. In the case of the structure analyzed in present paper the reduction of the bending moments for E_f = 80,000 kPa versus E_f = 40,000 kPa is in the range 13%-27%.

Another aspect needing be pointed out is concerning the effect on seismic response of the water having 2,30 m depth from river channel placed over collector. Its effect appears to be very important. Under action of DSH + DSV, the bending moments in collector structure increase in the range 32%-120% when there is water in river channel versus the case when the river channel is empty. If over embedded structure was soil instead of water, the effect should be possible diminished because of arches discharge that may arise in the field above the structure.

The comparison between corresponding results which were obtained in spectral analysis and direct time integration method (Fig. 8) emphasizes that spectral analysis led generally to higher values, so it is conservative. This conclusion is confirmed by other numerous applications [4, 5].

Concerning the capacity of the collector structure to withstand to Bucharest Vrancea 4.03.1977 earthquake,

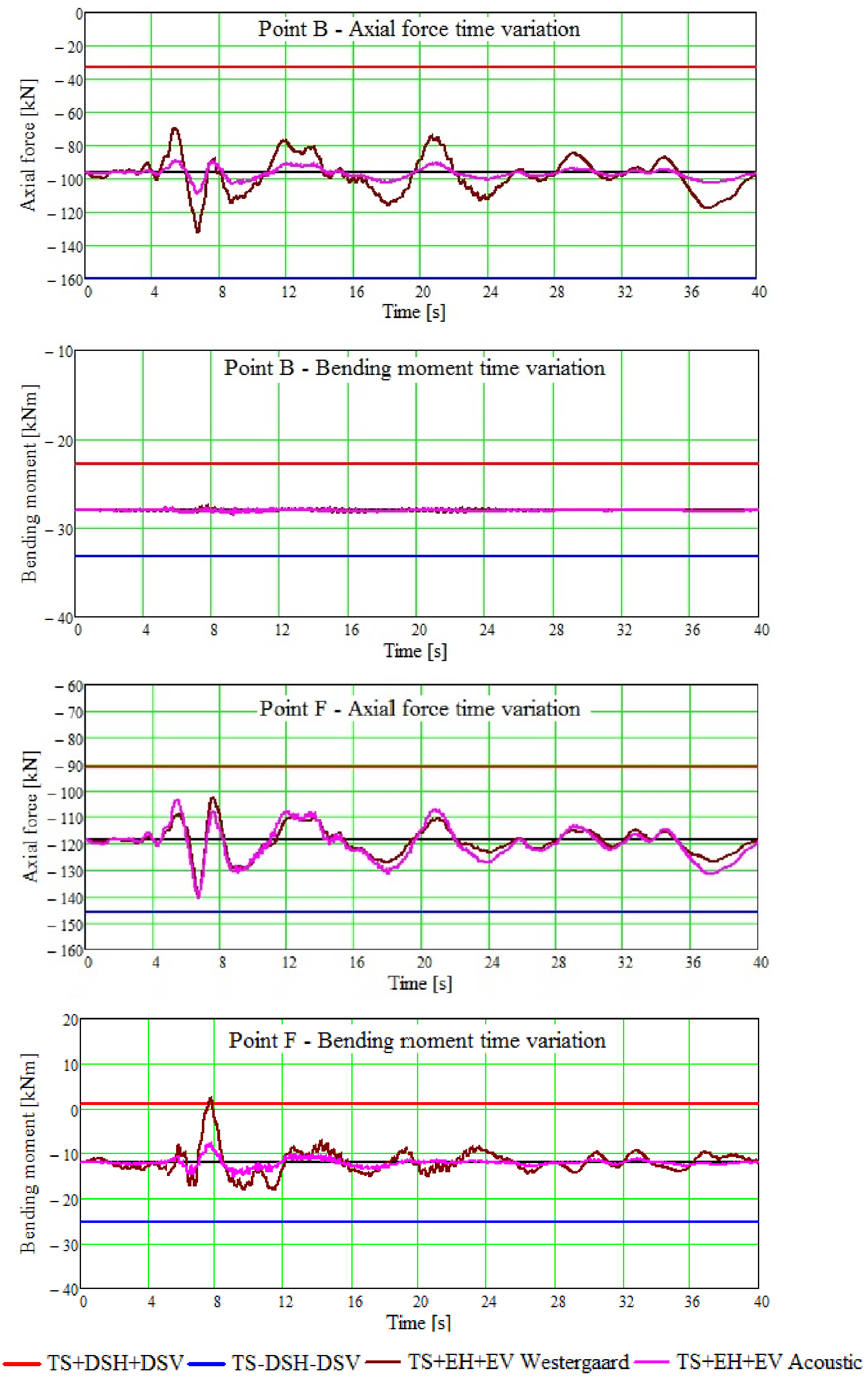


Fig. 8 Bucharest wastewater main collector—Axial forces and bending moments time variation in B and F points (see Fig. 6a) to action of the Bucharest–Vrancea 4.03.1977 N-S and V earthquake.

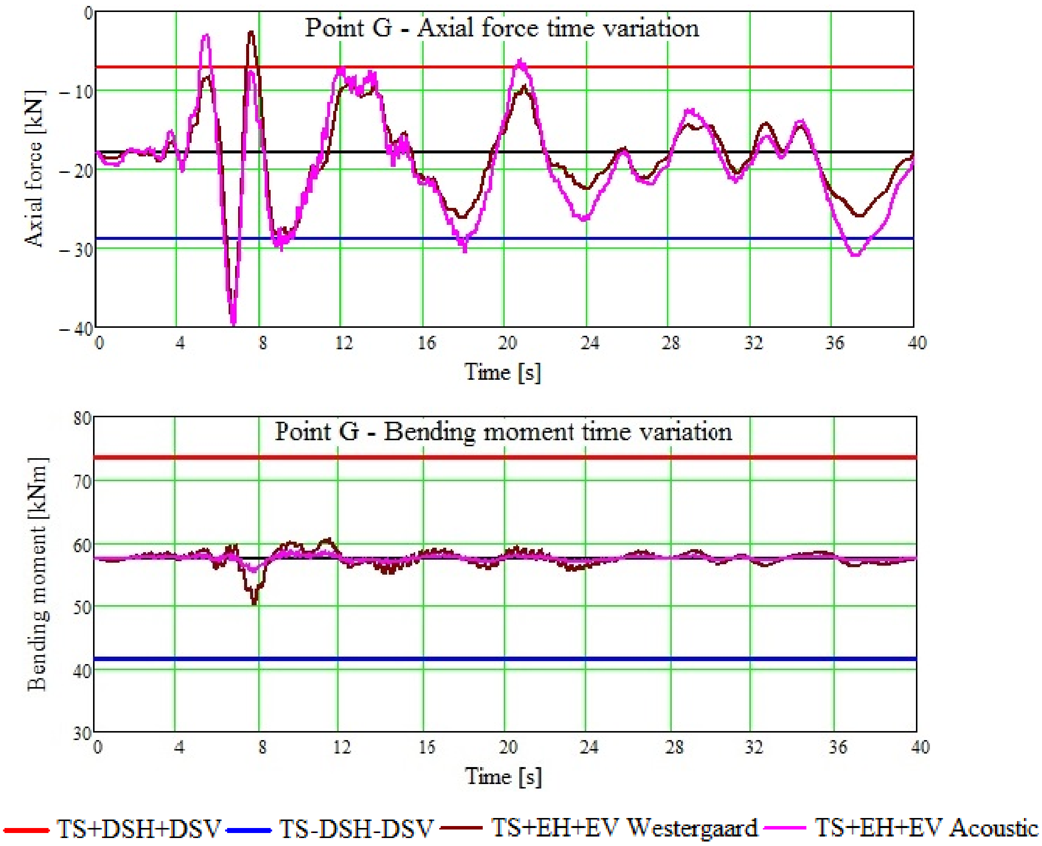


Fig. 9 Bucharest wastewater main collector—Axial forces and bending moments time variation in G point (see Fig. 6a) to action of the Bucharest–Vrancea 4.03.1977 N-S and V earthquake.

the conclusion is an optimistic one comparing the effective maximum sectional stresses on structure with structure resilience (capacity of resistance). The critical point of the structure seems to be central node wall-apron where maximum axial force developed during earthquake reaches the resilience of the wall. A potential collapse mechanism can consist of central wall collapse causing destruction of the floor.

4. Concluding Remarks

The mechanical characteristics of the soil surrounding an embedded structure have important effects on seismic response of the structure. In seismic response of embedded (buried) structures the kinematic interaction is frequently more important than inertial soil—structure interaction. In the analysis presented in this paper the fundamental period of a large wastewater collector increased with about 40% and bending moments in its structural elements increased in the range 13%-27% when surrounding soil bulk modulus varied from 80,000 kPa to 40,000 kPa.

In the analysis cited before needs remark also the very important influence on seismic response of the water having 2.30 m depth from a river channel located over wastewater collector. The bending moments in collector structure increased in the range 32%-120% when there was water in river channel versus the case when the channel was empty. This effect remains important also if over buried structure exists soil although the effect can be slightly reduced by arches discharge.

The present study was performed in the hypothesis of linear elastic behavior of materials from soil-structure system. This is a conservative hypothesis. More sophisticated constitutive relations (nonlinear, elasto–plastic etc.) concerning material behavior could reveal additional reserve of the structure resistance but they were not applied in present paper because of lack of adequately field measurements.

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