UDC: 625.78
Stručni članak

DYNAMIC SOIL-PIPELINE INTERACTION INDUCED BY HIGH-SPEED TRAFFIC UNDER ENVIRONMENTAL EFFECTS: TWO COMPUTATIONAL APPROACHES

A. Liolios [1], K. Liolios [2], B. Folic [3], K. Georgiev [4] & I. Georgiev [5]

[1] *Democritus University of Thrace, Dept. Civil Engineering, Xanthi, Greece,*
e-mail: aliolios@civil.duth.gr
[2] *Institute of Information and Communication Technologies,*
Bulgarian Academy of Sciences, Sofia, Bulgaria
e-mail: kostisliolios@gmail.com, kliolios@civil.duth.gr
[3] *University of Belgrade, Fac. of Mech. Enging, Belgrade, Serbia,*
e-mail: boris.folic@gmail.com,
[4] *Institute of Information and Communication Technologies,*
Bulgarian Academy of Sciences, Sofia, Bulgaria
e-mail: georgiev@parallel.bas.bg
[5] *Institute of Information and Communication Technologies and*
Institute of Mathematics and Informatics,
Bulgarian Academy of Sciences, Sofia, Bulgaria
e-mail: ivan.georgiev@parallel.bas.bg

Dedicated to the memory of Yordan MILEV, (15.2.1960 - 8.1.2017), Late Professor at the University of Architecture, Civil Engineering and Geodesy (UACEG), Sofia, Bulgaria.

ABSTRACT

The paper deals with two computational approaches for the unilateral contact problem of dynamic soil-pipeline interaction induced by high-speed moving loading sources. Unilateral contact effects due to tensionless soil capacity, soil elastoplastic-fracturing behaviour and gapping, which may be significant, are strictly taken into account, as well as environmental effects decreasing the soil resistance. The first numerical approach, called inequality approach, is based on a double discretization, in space by the Finite Element Method combined with Boundary Element Method, and in time, and on nonconvex optimization. By convolutional procedures, the number of the problem unknowns is significantly reduced and a nonconvex linear complementarity problem is solved in each time-step. The second numerical approach, called incremental approach, uses the Ruaumoko structural engineering software. Both presented methods are useful in geotechnical praxis for the resistant construction, design and control of buried pipelines against man-made soil vibrations as well as seismic excitations.

KEY WORDS. Dynamic soil-structure interaction, Unilateral contact, Environmental Degradation, Numerical geotechnical engineering

INTRODUCTION

Man-made soil vibrations may significantly influence the dynamic response of buildings and various other structures. So, vibrations generated by loads moving on a railway track on layered ground, underground explosion-induced stress and/or displacement wave propagation in a surrounding soil-environment and high-speed train induced ground vibrations around tunnels are some examples of such man-made soil vibrations, see e.g. [1-5]

On the other hand, soil degradation caused by environmental pollution [6] may significantly influence the soil-structure interaction under static and/or dynamic actions. Especially for pipelines (life-line networks, tunnels etc.), this degradation of the strength quality of the surrounding soil-environment during earthquake excitations can cause significant changes as concerns their seismic response [3].

Dynamic soil-pipeline interaction due to as above soil excitations is also a problem in structural and geotechnical engineering related to the wave propagation, moving loads and, from socio-economic points of view, to vibration reduction. In previous papers [12,13], the dynamic and seismic (so, a nature-made soil vibration) soil-pipeline interaction had been considered as one of the so-called inequality problems of structural engineering. As wellknown [11-15,17-19, 23-24, 27-28], the governing conditions of these problems are equalities as well as inequalities. Indeed, for the case of the general dynamic soil-structure interaction, see e.g. [1,11-13], the interaction stresses on the transmitting interface between the structure and the soil are of compressive type only. Moreover, due to in general nonlinear, elastoplastic, tensionless, fracturing etc. soil behaviour, gaps can be created between the soil and the structure. Thus, during strong earthquakes, separation and uplift phenomena are often appeared, as the praxis has shown [4, 9, 20, 26, 29].

The mathematical treatment of the so-formulated inequality problems can be obtained by the variational and/or hemivariational inequality approach. Numerical procedures, based on the above approach, for numerous dynamic inequality problems of structural engineering have been also presented, see e.g. [9, 11,17-19, 23-25, 27].

The present paper deals with two numerical procedures for the inequality dynamic problem of buried pipelines under horizontal ground excitation, perpendicular to the pipeline axis. Degradation of the surrounding soil caused by environmental actions is taking into account. In the problem formulation, the above considerations about gapping as well as soil elastoplastic softening behaviour are taken into account. Both proposed numerical procedures are based on a double discretization, in space and time. The first procedure uses methods of nonlinear programming. Thus, in each time-step a non-convex linear complementarity problem involving a reduced number of the problem unknowns is solved. The second procedure is an incremental one and uses the Ruaumoko software [21]. Finally, the two presented procedures are applied in a comparative way to an example problem of dynamic pipeline-soil interaction, caused by the wave propagation induced by high-velocity traffic in the surrounding soil.

THE PROBLEM FORMULATION

First, a discretization in space by combining the finite element method (FEM) with the boundary element one (BEM) is used for the soil-pipeline system [1,7-13,16]. The pipeline is discretized into frame-beam finite elements. Each pipeline node is considered as connected to the associate soil nodes on both sides through two *unilateral* (interface) elements. Every such *u-element* consists of an elastoplastic softening spring and a dashpot, connected in parallel (see e.g. the Figure 2), and appears a compressive force r(t) only at the time-moments t when the pipeline node comes in contact with the corresponding soil node. Let v(t) denote the relative retirement displacement between the soil-node and the pipe-node, g(t) the existing gap and $w_g(t)$ the soil displacement induced by moving sources of the type described in the Introduction. Then the piece-wise linearized unilateral contact behaviour of the soil-pipeline interaction is expressed in the compact form of the following linear complementarity conditions:

$$v+g+w_g \geq 0, \quad r \geq 0, \quad r.(v+g+w_g) = 0. \tag{1}$$

Further, the *u-element* compressive force is in convolutional form [1]

$$r = S(t)*y(t), \quad y = w - (g + v), \tag{2a,b}$$

or in form used in Foundation Analysis [17]

$$r = c_s . (dy/dt) + p(y). \tag{2c}$$

Here c_s is the soil damping coefficient, w = w(t) the pipeline node lateral displacement, y = y(t) the shortening deformation of the soil-element, and p(y) the spring force. By * is denoted the convolution operation. S(t) is the dynamic stiffness coefficient for the soil and can be computed by the BEM [1]. Function p(y) is mathematically defined by the following, in general nonconvex and nonmonotone constitutive relation:

$$p(y) \in C_g P_g (y), \tag{2d}$$

where C_g is Clarke's generalized gradient and P_g ( ) the symbol of superpotential nonconvex functions [17-19]. So, (2d) expresses in general the elastoplastic-softening soil behaviour, where unloading-reloading, gapping, degrading, fracturing etc. effects are included.

For the herein numerical treatment, p(y) is piece-wise linearized in terms of non-negative multipliers as in plasticity [14,15,28]. So the dynamic equilibrium conditions for the assembled soil-pipeline system are written in matrix form as follows:

$$\underline{M}\, \underline{\ddot{u}}(t) + \underline{C}\, \underline{\acute{u}}(t) + \underline{K}\, \underline{u}(t) = \underline{f}(t) + \underline{A}^T \underline{r}(t), \tag{3}$$

$$\underline{h} = \underline{B}^T\underline{r} - \underline{H}\,\underline{z} - \underline{k}, \quad \underline{h} \le \underline{0}, \quad \underline{z} \ge \underline{0}, \quad \underline{z}^T.\underline{h} = 0. \tag{4}$$

Here, eq. (3) is the dynamic matrix equilibrium condition and eqs. (4) include the unilateral and the piece-wise linearized constitutive relations. Dots over symbols denote, as usually, time-derivatives. $\underline{M}$, $\underline{C}$ and $\underline{K}$ are the mass, damping and stiffness matrix, respectively; $\underline{u}$, $\underline{f}$ are the displacement and the force vectors, respectively; $\underline{A}$, $\underline{B}$ are kinematic transformation matrices; $\underline{z}$, $\underline{k}$ are the nonnegative multiplier and the unilateral capacity vectors; and $\underline{H}$ is the unilateral interaction square matrix, symmetric and positive semidefinite for the elastoplastic soil case. But in the case of soil softening, some diagonal entries of $\underline{H}$ are nonpositive [28]. Finally, the force vector $\underline{f}$ includes the effects due to high-speed moving sources in the surrounding soil along the pipeline.
Thus the so-formulated problem is to find ($\underline{u}$,$\underline{r}$,$\underline{g}$,$\underline{z}$) satisfying (1)-(4) when $\underline{f}$ and suitable initial conditions are given.

THE TWO COMPUTATIONAL PROCEDURES

Two computational methods, the inequality one and the incremental one, are next presented for the numerical solution of the previously formulated problem, concerning the dynamic response of buried pipelines against man-made soil vibrations as well as seismic excitations.
The first procedure, the so-called *inequality* one, is based on the convolutional approach of [13]. Assuming that the unilateral quantities $\underline{z}$ and $\underline{h}$ include all local nonlinearities and unilateral behaviour quantities,. and applying the central-difference time discretization, and after suitable elimination of some unknowns, we arrive eventually at

$$\underline{h}_n = \underline{D}\,\underline{z}_n + \underline{d}_n, \quad \underline{z}_n \ge \underline{0}, \quad \underline{h}_n \le \underline{0}, \quad \underline{z}_n^T.\underline{h}_n = 0. \tag{5}$$

Thus, at every time-moment $t_n = n.\Delta t$, where Δt is the time step, the problem of rels. (5) is to be treated. This problem is a *Non-Convex Linear Complementarity Problem* (NCLCP), can be treated as an hemivariational one and is solved by available methods and computer codes of nonconvex optimization [18-19, 23-24]. So, in each time-step Δt we compute which of the unilateral constraints are active and which are not. Due to soil softening, the matrix $\underline{D}$ is not a strictly positive definite one in general. But as numerical experiments have shown, in most civil engineering applications of soil-pipeline interaction this matrix is P-copositive. Thus the existence of a solution is assured [12-15, 17-19, 23-25, 27,28].
The second procedure, the so-called *incremental* one, is based on the incremental formulation and solution of the problem. So, the dynamic equilibrium conditions for the assembled soil-pipeline system are written in matrix form as follows:

$$\underline{M}\,\Delta\underline{\ddot{u}}(t) + \underline{C}\,\Delta\underline{\dot{u}}(t) + \underline{K}_T\Delta\underline{u}(t) = \Delta\underline{f}(t) + \underline{A}^T\,\Delta\underline{r}(t), \tag{6}$$

where by $\underline{K}_T$ is denoted the current tangential stiffness. Now, for the numerical treatment, use is made of the Ruaumoko structural engineering software [21]. This code provides a large library of many different hysteresis rules to represent the inelastic behaviour of frame and spring members. For further details see [21].

So, the ‘bilinear with slackness’ model shown in Fig. 1 can be used to represent the unilateral behaviour of the interface elements by suitable choice of the parameter values. Thus, for the simulation of the behaviour of the interface *unilateral* soil-elements, and in order to be appeared a compressive force F(t) only, in the ‘bilinear with slackness’ hysteresis rule model of Fig. 1 the parameter values are: F_{y+} =0.0 and r_+ = 0.0.

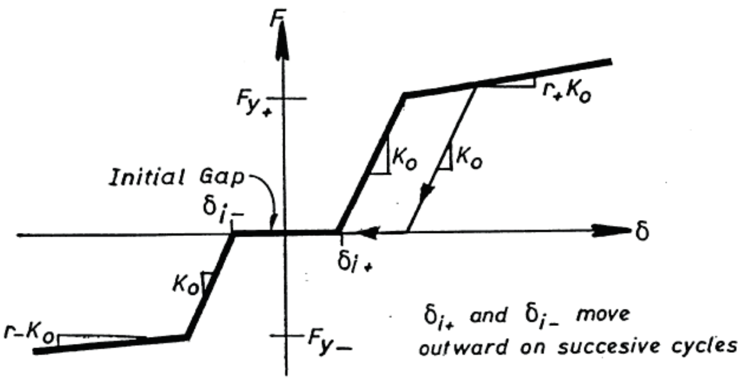

Figure 1. The ‘bilinear with slackness’ hysteresis rule model in Ruaumoko [21].

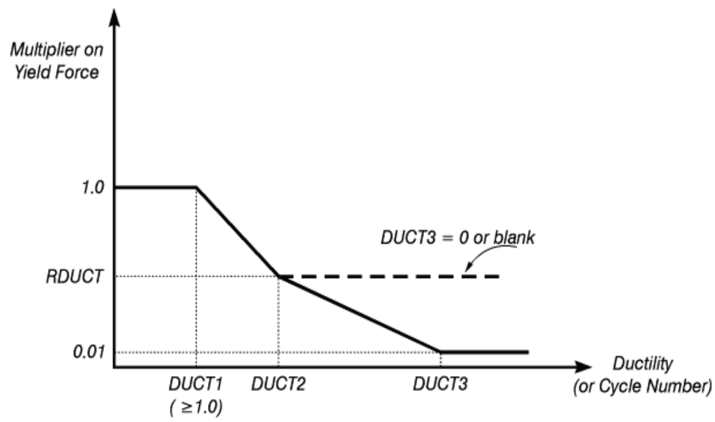

Figure 2. The degrading strength rule in Ruaumoko [21].

Moreover, stiffness and strength degradation are simulated in Ruaumoko by using suitable stiffness degrading (e.g. Takeda model) and strength degrading hysteresis rules. In Fig. 2 is shown the degrading strength rule, which provides the strength reduction variation in terms of either ductility or cycle number.

NUMERICAL EXAMPLE

The numerical example of [13] was treated by the inequality approach. It is reconsidered here for comparison reasons concerning the application of the incremental approach.
The example deals with an empty horizontal steel circular pipeline of length L = 200 m, outside diameter 1 m, thickness 1.5 cm, elastic modulus $21*10^7$ KN/m^2 and yield stress 50 KN/cm^2 is considered. As depicted in Figure 3, the pipeline is clamped by the two anchor blocks A and B imbedded into a rock soil. The soil, into which the horizontal pipeline is buried, has an elastoplastic behaviour as in Figure 4 and consists of two regions: the first (I) is soft with a shear modulus $G_i = 5000$ KN/m^2, the second (II) is hard with a shear modulus $G_{ii} = 100000$ KN/m^2. The parameters for the elastoplastic behaviour in Figure 2 are taken to be $a = p_u.b$, $b = 100$ m^{-1}, where it is $p_u = 100$ KN/m^2 for the soft region (I) and $p_u = 2000$ KN/m^2 for the hard region (II). The difference of the behaviour in the two regions (I) and (II) is caused by environmental actions.

Further, due to some high-speed moving sources of soil vibration, the ground excitation is assumed to be a sinusoidal horizontal wave propagation parallel to the pipeline axis (Figure 2), with mean speed $v_g = 0.4$ km/sec in the soft region (I) and $v_g = 0.8$ km/sec in the hard one (II), frequency $f_g = 10$ rad/sec, duration $T = 2\pi/f_g$ and maximum ground displacement $w_o = 5$ cm. Thus the horizontal ground motion, perpendicular to the pipeline axis x, is expressed mathematically by the following relation, where H(t) is the Heaviside function:

$$u_g(x,t) = w_o \sin(t-x/v_g) . \{H(t-x/v_g)-H(t-x/v_g-T)\}. \quad (7)$$

Some indicative results from the numerical ones, obtained by applying the two presented procedures, are here reported. Both methods have provided a good agreement of their results. So in Figure 5 the gaps along the pipeline due to permanent soil deformations are shown for the time moments $t_1 = 0.6$ sec and $t_2 = 2.1$ sec. The difference of the gap widths in the soft and in the hard soil region is remarkable. Because of these created gaps, for a subsequent soil excitation the part of the pipeline in the soft region may not have a behaviour of a beam fully supported by foundation. On the other hand, in Figure 6 it is shown the distribution of the soil-pressures at the time $t_1 = 0.60$ sec. The stresses are smaller in the soft region than in the hard one. Furthermore, a concentration of stresses is observed around the pipeline middle C, where the soil quality changes.

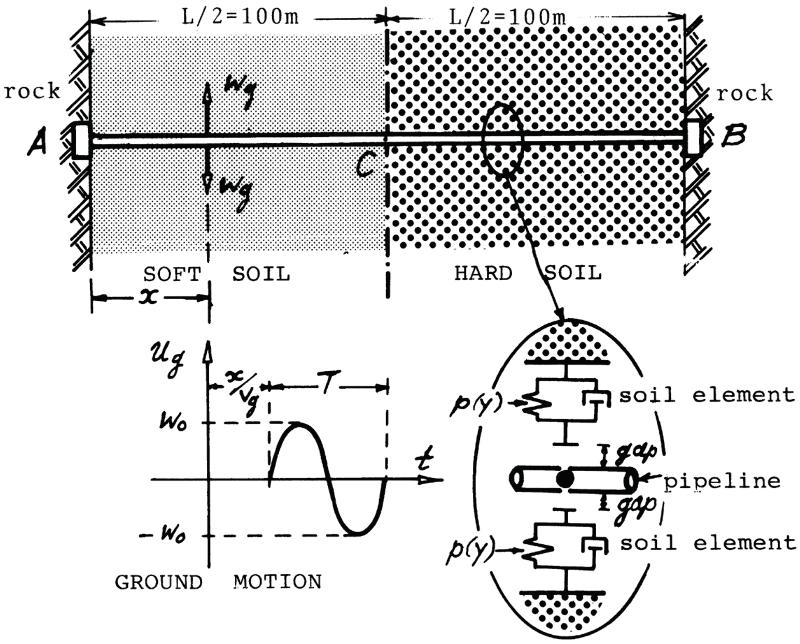

Figure 3. Soil-pipeline system, horizontal wave travelling ground motion and soil-pipeline interaction modelization.

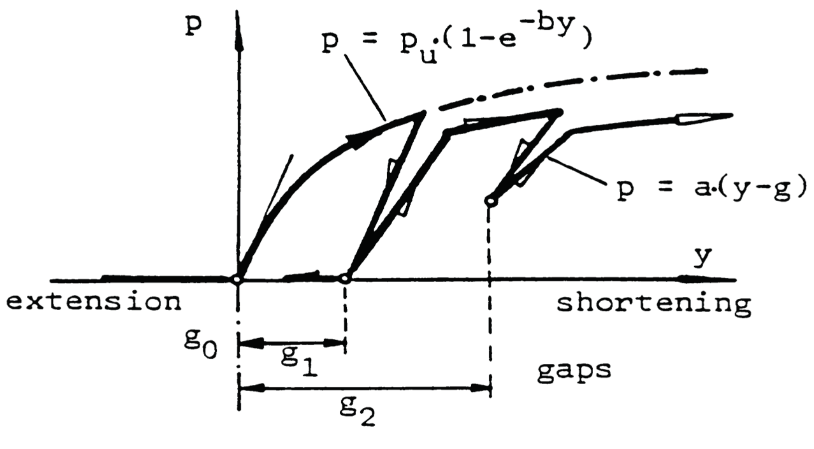

Figure 4: Unilateral, degradating soil behaviour in loading-unloading with remaining gaps.

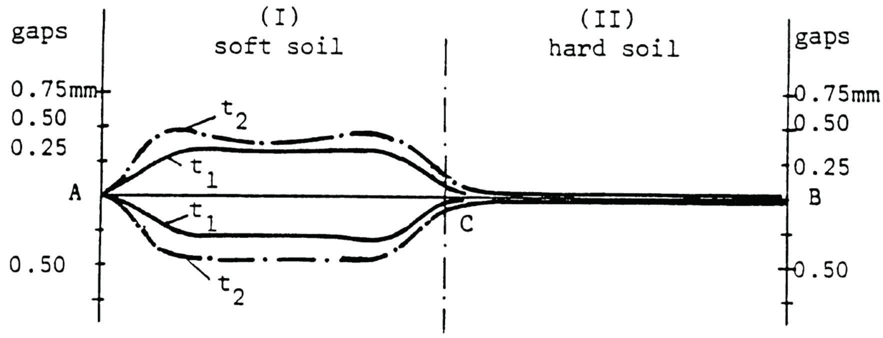

Figure 5. Gaps along the pipeline at times t_1 = 0.6 sec and t_2 = 2.1 sec.

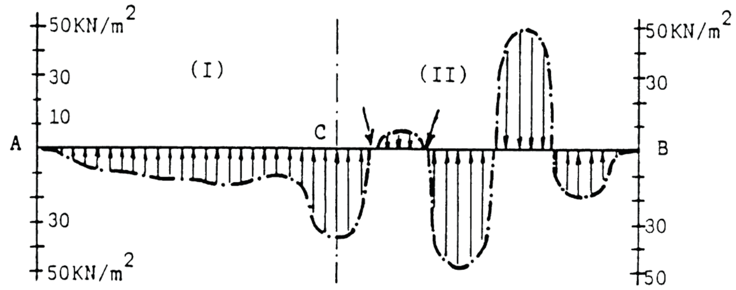

Figure 6. Soil-pressure distribution at the time t_1 = 0.6 sec

CONCLUDING REMARKS

Two computational methods, the inequality one and the incremental one, have been presented for the dynamic response of buried pipelines against man-made soil vibrations as well as seismic excitations. As the indicative results of an numerical example show, unilateral contact effects due to tensionless soil capacity and to gapping may be significant and have to be taken into account for the resistant construction, design and control of buried pipelines against man-made soil vibrations.

These unilateral contact effects can be numerically estimated by the herein presented procedures, which is realizable on computers by using existent codes of the finite element method (FEM), and of optimization algorithmes. Both presented methods are useful in geotechnical praxis for the resistant construction, design and control of buried pipelines against man-made soil vibrations as well as seismic excitations.

Acknowledgment:
Concerning the co-authors K. Liolios, K. Georgiev and I. Georgiev, this work was partially supported by the Bulgarian Academy of Sciences through the "Young Scientists" Grant No. DFNP-97/04.05.2016.

REFERENCES

1. Wolf, J.P. 1998. *Soil-Structure-Interaction Analysis in Time Domain*. Englewood Cliffs, N.J.: Prentice-Hall.
2. Scott, R., *Foundation Analysis*. London: Prentice-Hall, (1981).
3. Cassaro, M.A. (ed.), *Lifeline Earthquake Engineering*, Proc. 3rd U.S.A. Conf., ASCE, New York (1991).
4. Savidis, S.A. & Bode, C., *Three-Dimensional Time Domain Analysis of Moving Loads on Railway Tracks on Layered Solis with Partial Uplift.* In: Schmid, G. & Chouw, N. (eds.), *WAVE2000, Proc. Int. Symp.* Bochum, Germany, 13-15 Dec.2000. Rotterdam: Balkema (2000).
5. Profillidis, V.A., *Railway Engineering.* Aldershot, Sydney, Avebury Technical, (1995).
6. Tchobanoglous, G., Peavy, H. & Rowe, D., *Environmental Engineering*, MacGraw-Hill, New York (1985).
7. Milev, N. (2016), *Soil-structure interaction*, PhD Thesis, UACEG, Sofia,(in Bulgarian).
8. Kazakov, K., I. Stoynova, Matuski, V. & Handruleva, A., (2016). *On the computational dynamic soil-strucure interaction (SSI) concepts in time-domain*. In: Folic R. (Ed), *Proceedings of 5th International Conference "Earthquake Engineering and Engineering Seismology"*. Sremski Karlovci, Serbia, 29-30 June 2016, pp. 371-378.
9. Baniotopoulos, C.C., Optimal control of above-ground pipelines under dynamic excitations, *Int. Jnl Pressure Vessel & Piping* **63**, 211-222, (1995).
10. Beskos, D.E., Boundary element methods in dynamic analysis: Part II (1986-1996), *Applied Mechanics Reviews*, Vol. 50, 149-187, (1997).
11. Antes, H. & Panagiotopoulos, P.D., *The Boundary Integral Approach to Static and Dynamic Contact Problems. Equality and Inequality Methods*,, Basel, Boston, Berlin: Birkhäuser Verlag, (1992).
12. Liolios A., Liolios K**.** and Michaltsos G. (2013). *A numerical approach to the non-convex dynamic problem of steel pile-soil interaction under environmental and second-order geometric effects*. Lecture Notes in Applied and Computational Mechanics, vol. 56, pp. 369-375.
13. Liolios, A. & Pitilakis, K. & Savidis, S. & Yeroyianni, M. *A convolutional numerical approach to the unilateral contact problem of seismic soil-pipeline interaction*. In: Bisch, P. & Labbe, P. & Pecker, A. (eds.), *Proceedings of the 11-th European Conference on Earthquake Engineering,* Abstract Vol., p.420. Paris, France, 6-11 Sept. 1998. Rotterdam: Balkema, (1998).
14. Maier, G., Grierson, D. E., & Best, M. J. (1977). Mathematical programming methods for deformation analysis at plastic collapse. *Computers & Structures*, *7*(5), 599-612.
15. Maier, G., Mathematical Programming Methods in Structural Analysis, in: Brebbia, C. and Tottenham, H., (Eds.),*Variational Methods in Engineering*, Vol.II, pp. 8/l-8/32, Southampton: Southampton Univ. Press, (1973).
16. Manolis, G.D. & Beskos, D.E., Underground and lifeline structures, in: Beskos, D.E. and Anagnostopoulos, S.A. (eds), *Computer Analysis and Design of Earthquake Resistant Structures*, pp. 775-837, Southampton: Comput. Mech. Publics, (1997).
17. Mistakidis, E.S. & Stavroulakis, G.E., *Nonconvex optimization in mechanics. Smooth and*

nonsmooth algorithmes, heuristic and engineering applications. Kluwer, London (1998).
18. Panagiotopoulos, P.D., *Inequality problems in mechanics and applications. Convex and nonconvex energy functions.* Birkhäuser Verlag, Boston-Basel-Stuttgart (1985).
19. Panagiotopoulos, P.D. *Hemivariational inequalities. Applications in Mechanics and Engineering.* Berlin, Springer (1993).
20. Patel. P.N. & Spyrakos, C.C., Uplifting-sliding response of flexible structures to seismic loads, *Engineering Analysis with Boundary Elements*, 8, 185-191 (1991).
21. Carr A.J., (2008). *"RUAUMOKO - Inelastic Dynamic Analysis Program".* Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.
22. Liolios A., Liolios K., Folic B., Georgiev K. and Georgiev I. (2017). A computational approach for the seismic upgrading of old RC structures by ties under shear effects. In: Folic R. (Ed), *Proceedings of 10th International Conference of Association of Civil Engineers of Serbia (ACES) "Assessment, Maintenance and Rehabilitation of Structures and Settlements".* Vrsac, Serbia, 14-16 June 2017.
23. Stavroulakis, G.E., Computational Nonsmooth Mechanics: Variational and Hemivariational Inequalities. *Nonlinear Analysis. Theory, Methods and Applications* 47/8, 5113-5124, (2001).
24. Stavroulaki, M.E. & Stavroulakis, G.E., Unilateral contact applications using FEM software. *Int. Jnl Appl. Mathem. & Comp. Sciences,* in print (2002).
25. Liolios A., Liolios K., Folic B., Georgiev K. and Georgiev I. (2016). Choice of the optimal ties system concerning the seismic upgrading of RC structures under multiple earthquakes. In: Folic R. (Ed), *Proceedings of 5th International Conference "Earthquake Engineering and Engineering Seismology".* Sremski Karlovci, Serbia, 29-30 June 2016, pp. 443-452.
26. Folic B., Ladjinovic, G., Folic R., Cosic, M. (2016). *.Pile-soil-pile interaction in designing the foundation of RC structures*. pp. 379- 386, In: Folic R. (Ed), *Proceedings of 5th International Conference "Earthquake Engineering and Engineering Seismology".* Sremski Karlovci, Serbia, 29-30 June 2016.
27. Liolios, A. A. (2000). *A linear complementarity approach for the non-convex seismic frictional interaction between adjacent structures under instabilizing effects.* Journal of Global Optimization, 17(1), 259-266.
28. Maier, G. (1971). *"Incremental plastic analysis in the presence of large displacements and physical instabilizing effects".* Int. J. Solids Struct. 7, 345–372.
29. Milev, I. (2016). *Practical application of EUROCODE 8 in seismic design of RC frame- and wall-structures.* In: Folic R. (Ed), *Proceedings of 5th International Conference "Earthquake Engineering and Engineering Seismology".* Sremski Karlovci, Serbia, 29-30 June 2016, pp. 1-34.