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LESSONS LEARNED FROM SOIL-STRUCTURE INTERACTION

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Abstract

The paper deals with the recurrence that naturally occurs between deformable structures and the bearing soil. In one of his preserved sketches Leonardo da Vinci assumed that there are loaded beams that deform under nearly parabolic shapes. The first mathematical model about the beams on elastic foundation is due to the German railroad engineer Emil Winkler in 1867 when he was teaching Strength of Materials at the Polytechnic Institute in Prague. It is a linear model independently of time that seems inspired from the Law of Elasticity published by Robert Hooke in 1678 as Ut tensio, sic vis, *and meaning* As the extension, so the force. *It looks like Winkler only replaced the tension by compression in Hooke's Law. By coincidence, in the same year 1867 Joseph Monier from Versailles obtained in Paris his patent for reinforced concrete. Winkler's Theory of beams on elastic foundations under static loads was gradually extended on thin and thick plates, piles and sheet piles, circular tanks and reinforced pipes. Later the elastic stability and dynamic behavior of the same structures was developed. In order to simplify the non-linear analysis in 1997 the finite difference theory was successfully introduced. All results of non-linear analysis are strongly influenced by the bi-local boundary conditions of Sturm-Liouville type. The practical consequence of this analysis consists in the need to provide appropriate joints between structures. There are simple joints with one degree of freedom only, for horizontal thermal contraction/expansion or vertical gravity settlement and seismic joints with six degrees of freedom, i.e. three translations and three rotations. For including in any analysis, the foundation soil should be carefully investigated by geotechnical and geology techniques. Particularly, the foundation soil in Bucharest requires high attention and competence in practical use. For evaluating the behavior in time of bearing soil, its viscous properties have to be accordingly considered in analyses. Soil-structure interaction is controlled by a legislation that satisfies the European Standards. All the existing study cases confirm that in Civil Engineering, sooner or later, any mistake should be paid.*

Key words: *critical infrastructure, degree of freedom, elastic foundation, seismic joint, settlement..*

INTRODUCTION

Human relation with foundation soil is lasting since the Megalithic Civilization in Egypt and Middle East. Later on, an incipient science of building, mainly based on the equilibrium in the gravitational field, was developed. The few ancient buildings that have been preserved from those old times prove their laws of discharging were correctly understood. Most of them disappeared due to different faults, wrong foundation concepts including. It is, for instance, the case of the Babel Tower. Built up during the reign of Hammurabi the Great (1792-1750 BCE), on soft foundations made of adobe masonry in a weak and oozy soil, after the death of Alexander the Great (356-323 BCE) the Tower reached an advanced state of damage and was abandoned. One of the first lessons of founding the buildings is due to Archimedes from Syracuse (287- 212 BCE). After discovering the lever he stated his ability to move with that device the Earth if a supporting point will become available. But such a miracle never happened. A building cannot be discharged on the foundation soil with the aid of a force, directly applied on a point, as a vector. Only a force applied upon a surface, as a pressure and tensor can practically complete such a task. This lesson remained as a golden rule for generations of builders. Most of the knowledge that Greeks and Romans accumulated during ancient history in foundation engineering was lost during the Middle Ages. Only in Renaissance the interest for the art of building was resumed and further developed. Leonardo da Vinci (1452-1519), who was greatly interested in Mechanics, observed that the foundation beams were bent together with the deformations assumed by supporting soil. He initiated several testing programs aimed to enrich the knowledge of building more consciously. Galileo Galilei (1564-1642) extended the experimental research. Based on the obtained results he published the book “Two New Sciences” as a synthesis of the knowledge of his époque. Rather soon after Galileo, in England, Robert Hooke (1635-1703) discovered the Law of elasticity as *Ut tensio, sic vis* meaning *As the extension, so the force.* It was published in 1678 in the paper suggestively entitled *De Potentiâ Restitutiva.* At the middle of eighteen century, during the so called Industrial Revolution that occurred in England, many technical innovations came to surface. In the next century the first railway networks were created. Due to the experienced gained in railway engineering, in 1867 Emil Winkler (1835-1888) published in Prague his Theory about beams on elastic foundations. By coincidence, in the same year 1867 Joseph Monier from Versailles obtained in Paris his patent for reinforced concrete. Since that year the history of controlled soil-structure interaction started.

The paper deals mainly with the lessons identified by five doctoral students and that were presented in their dissertations during last six years. With those occasions the lessons from the rich experience of the two Romanian famous builders Aurel A. Beleș (1891-1976) and Emil Prager (1888-1985) were also mentioned . The data have been obtained from the existing engineering works in Bucharest or country side and are of practical interest either for designers or researchers. The two existing actions, in the original Newtonian approach, that were considered in the paper, are the long lasting actions and the short time ones. According to Eurocode 1, and Romanian Code CR 0-2012 as well, they are classified as permanent and accidental actions. The first ones are of gravitational origin while the second are mainly generated by earthquakes. The lessons selected for paper refer to the types of foundations and their depths, the shape and size of the buildings they are supporting, the joints between them and seismic tests. Finally, the economic effects of soil-structure interaction, higher education matters and legislation provisions are briefly commented.

WINKLER’s THEORY

As a young employee to a railway society Emil Winkler, at only 32 years, was fascinated by the dance of steel rails under the wheels of passing trains. Well educated in structural engineering at Dresden Polytechnic he was aware by Hooke’s law of elasticity. Under the evidence of seen rails he had the inspiration to replace in Hooke’s law the tension with compression. In addition he took the courage to assimilate the elastic rails with foundation beams. The rest what followed was mathematics. Winkler adopted a simply linear model of analysis . Indeed, the intensity of soil reaction $p(x)$ to the loads applied upon a continuously supported beam is proportional with the vertical deformation $v(x)$, common to both soil and beam, i.e.

$$p(x) = -kv(x) \quad (1)$$

where k is the characteristic modulus of soil assumed constant. Whether the stiffness of beam EI_z is also constant along the beam length, then from the simplified equation of bending, due to Euler-Bernoulli, one obtains

$$EI_z \frac{d^4 v}{dx^4} + kv = 0 . \quad (2)$$

With the aid of notation

$$\frac{k}{EI_z} = 4\beta^4 \rightarrow \beta = \sqrt[4]{\frac{k}{4EI_z}} \quad (3)$$

where β is called *damping factor* and is measured in m^{-1}, the previous equation (3) takes the form

$$\frac{d^4 v}{dv^4} + 4\beta^4 v = 0 . \quad (4)$$

This homogeneous equation assumes a general solution like this one

$$\begin{aligned} v(x) = e^{-\beta x}(A\cos\beta x + B\sin\beta x) + \\ + e^{+\beta x}(C\cos\beta x + D\sin\beta x) \end{aligned} \quad (5)$$

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Where the integration constants A, B, C, D are determined from both the bi-local conditions of Sturm-Liouville and the continuity conditions of Saint-Venant. Further the whole philosophy of soil-structure interaction is based on the above presented theory of Winkler.

STRUCTURAL APPLICATIONS

Winkler's Theory was extended from beams to thin and thick plane plates. The difference between the two types of plates is made in second case by sharing forces. Then, for computational purposes, Winkler's Theory was converted with aid of finite difference equations. They were associated with boundary and external support conditions, internal support conditions, prescribed displacements and decomposition process. This computational method was first applied to circular concrete tanks, circular tanks with sliding or pinned joints, circular tanks with walls integrated in their bases, temperature effects on the walls of circular tanks and pressurised concrete tanks. The subsequent group of applications regard laterally loaded single piles, pile groups and sheet piling. Finally, the last applications were devoted to aqueducts, base slabs of conventional retaining walls, continuous foundations and footings, and cross support beams. The available computing program entitled *Analysis of beams on elastic foundations* or shortly *bef* seems very useful.

The elastic medium has a favourable influence also on the stability of structural components. In the case of pile elastic stability the problem was simultaneously solved since 1914, independently by each other, by A. Beleș in Romania and S. Timoshenko in Rusia. The Eulerian critical force assumes the expression

$$P_{cr} = \frac{\pi^2 EI_z}{l^2}\left(n^2 + \frac{kl^4}{n^2\pi^4 EI_z}\right), \; n=1,\, 2,\, \ldots \qquad (6)$$

where the second term contains the contribution of the elastic soil.

Similarly, in the case of rectangular plane plates, with the sides *a* and *b,* the critical force one obtains by minimisation the expression

$$P = \left(\frac{m^2\pi^2}{a^2} + \frac{n^2\pi^2}{b^2}\right)D + \frac{k}{\frac{m^2\pi^2}{a^2} + \frac{n^2\pi^2}{b^2}}, \; m\ n=1,\, 2,\, \ldots \qquad (7)$$

where

$$D = \frac{Eh_p^3}{12(1-\mu^2)} \qquad (8)$$

is the cylindrical stiffness of the plane plate of thickness h_p.

The dynamic response of the structural members on elastic medium was also similarly solved.

FOUNDATION SOILS

The soil devoted to foundation should fulfil three conditions: 1) No biodegradable contents; 2) No freezing influence and 3) Bearing capacity to compression. Usually, this information is obtained from a geotechnical study. In spite of NP 074/2007 provisions, regarding the homogeneity and uniformity of soil structure, all geotechnical studies are referring to the existence of soil layers. For current construction sites the infill layers are assumed to take the same thickness like the freezing depth that is untrue. For instance with the aid of geophysical devices it was determined that on a large zone around the Arch of Triumph in Bucharest the infill layer is strongly no uniform, and its depths randomly vary between 2.0 m and 3.0 m. A similar situation, but in less extended areas, can be meet in Cotroceni. And what in Capital happens, anywhere in the country could occur.

Another lesson that should draw attention refers to the soils of loess nature that are sensible to come moisten and getting damp. Frequently, some lentils of such soils were naturally inserted in the ordinary soils and if are not identified in due time they remain as hidden perils for buildings. Sometimes they are discovered during earthquakes by the caused damages. Romanian technical legislation is rich in provisions regarding the foundation soils and maintenance rules. Unfortunately, the basic education and elementary consciousness for applying these documents is still lacking. This remark equally

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refers to both private owners and official authorities.

TYPES OF FOUNDATIONS

Usually, there are three types of foundations: 1) isolated for columns, 2) continuous under walls and 3) base slabs as general foundations for basements or cellars. Long time ago they were made of stone or brick masonry. Nowadays only concrete and reinforced concrete are used for foundations. From gravitational reasons the soles of these foundations should be perfectly horizontal. When the foundation ground is horizontal is recommended that all foundations to be located at the same level while in the case of inclined grounds, horizontal steps will be provided. In weak soils, like those existing in Bucharest, the isolated foundations should be avoided, and locate the columns together with the walls on continuous foundations or directly on the base slabs. It would be good that all foundations of a building to be balanced in the gravitational field. That means a uniform disposition of foundations in the horizontal plane such as the vertical axis of building to fall either on or near the gravity centre of foundation plane. As long as the depth of foundation is concerned the freezing condition is not enough. There is an important proportion between the foundation depth and building height defined by the ratio 1:6. For buildings well balanced, with symmetric vertical planes for instance, and good foundation soils, this ratio can be reduced to 1:10 or even 1:12. On the contrary, for very irregular buildings that ratio should be increased to 1:5 or even 1:4. Regarding the upper parts of foundations that support building ground floors and called elevation it should be raised at least with 60 or 90 cm over the level of natural ground that surrounds the buildings. Visitors of the Village Museum, located not far by the University of Agricultural Sciences in Bucharest, can easily check out that this old rule is fulfilled without any exception by the exhibited buildings. Paradoxically, at the main building of the Faculty of Civil and Environmental Engineering, built in 1972, the level of building ground floor coincides with that of natural ground. The building neither provided with basement nor satisfies the above mentioned proportion what explains the severe damages that occurred under the 1977 earthquake. The reinforcing works carried on between the years 1987 and 1996 much improved building seismic safety. Generally, basements and cellars improve the soil-structure interaction. The contacts between buildings and foundation grounds are much closer. Without basements and cellars the building with shallow foundations are like boats freely floating on waters. It is the case of the old three-lobbed churches with soft foundations of brick masonry. Due to repeated settlements most of them display cracked walls and artificial wooden steeples because the original ones in masonry were cut by earthquakes.

BUILDING SHAPES AND SIZES

With population growth and its concentration in urban areas a large diversity of buildings does coexist as absolutely necessary. From the perspective of soil-structure interaction they are classified as low-raise, medium-raise and high-raise buildings. Fortunately, the existing advanced technology is able to provide structural solutions for appropriate foundations at proportional costs. There are however some foundation problems when one or more new buildings should be located in the vicinity of old, existing buildings. In addition the shapes of buildings in vertical and horizontal planes should be very carefully considered in seismic prone areas. It is the problem of irregularities which also involve the distribution of masses. The amount of irregularities is evaluated on the basis of distances or eccentricities between mass or gravity centres and rotation or rigidity centres. According to Eurocode 8 and Romanian National Code P100-1/2013 usually, the cross sections of buildings shaped in L, U, T and E forms arise problems. They develop large torsion moments that generate huge sharing forces. The only solution to avoid disasters in the case of new buildings is to divide the four critical shapes in smaller rectangular surfaces. The problem remains open in the case of old existing buildings improperly shaped. Often by inadequate reinforcing of such critical shapes the damaging danger of existing buildings increases.

STRUCTURAL JOINTS

The best lesson ever learned from earthquakes is about joints. Indeed, before the strong EQ that occurred on March 4th, 1977 only two types of joints were recommended in Civil Engineering, namely expansion joints with one degree of freedom, the horizontal displacement, and settlement joints also with one degree of freedom, the vertical displacement. According to a long tradition for many years the adjoining buildings were attached to each other along their blind walls, without any separation between them, like they would reciprocally support in case of danger. During that earthquake it came out that it was a wrong approach that should be immediately eradicated. This is why after 1977 the seismic joint was created, theoretically with six degrees of freedom, three translations and three rotations. All codes of seismic protection in the world adopted this provision. According to Romanian Code P100-1/2013, clause 4.6.2.7 (4), eq. (4.25), the joint width should assume the value

$$\Delta \geq \sqrt{d_{1\max}^2 + d_{2\max}^2} \qquad (9)$$

where d_1 and d_2 are the relevant displacements of the adjacent buildings or parts of the same building. It is worth to be known that seismic joints are not optional, but compulsory. The seismic joints should be included in programs of periodical maintenance and permanent monitoring. In the United States all strategic buildings are continuously supervised along their contours, delimited by joints, with GPS devices because earthquakes or terrorist attacks are unforeseeable. With the aid of seismic joints the response of buildings to earthquakes can be easily controlled and when necessary improve it by involving the soil-structure interaction. The study cases presented in four doctoral theses are summing up this statement [1, 2, 3, 4].

SEISMIC TESTS

Soil-structure interaction is a latent and subtle mechanical phenomenon. This is why any opportunity of experimental checking is of highest interest.

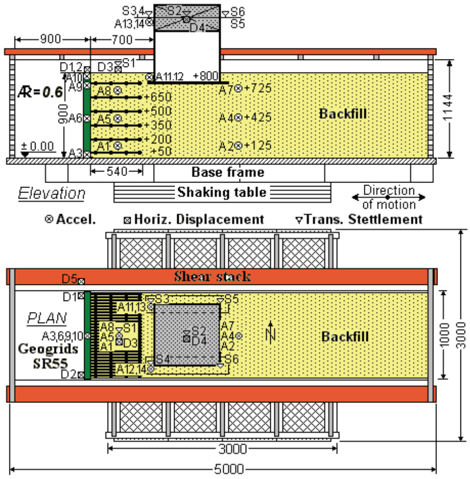

Figure 1. Conventional 3D model

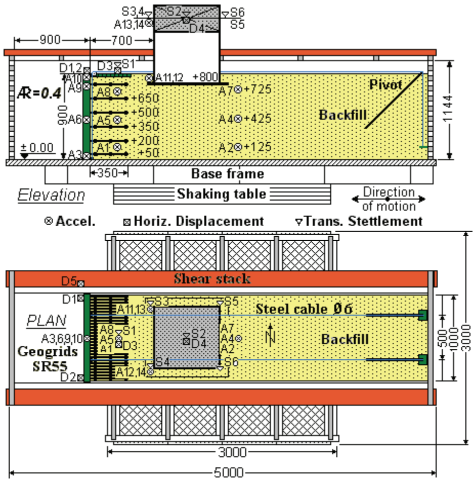

Figure 2. Confined 3D model

Figure 3. 3D model installed on the shaking table

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By winning the competition organized by the European Commission for a research project at the Laboratory of Seismic Engineering of Bristol University in UK, its task was devoted to soil-structure interaction.
Two 3D models, one conventional (Fig. 1) and another confined (Fig.2), supporting the same elastic structure of steel, were designed in Bucharest and comparatively tested on the shaking table of Bristol University (Fig. 3). Particularly, this shaking table was provided with an original sharing box patented by Dr. Adam Crewe from Bristol University.
Three types of dynamic excitations were used: harmonic sine (Fig. 4), El Centro '40 (Fig. 5) and Eurocode 8 artificial earthquake (Fig. 6)

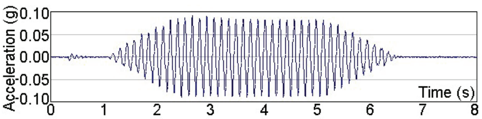

Figure 4. Harmonic sine

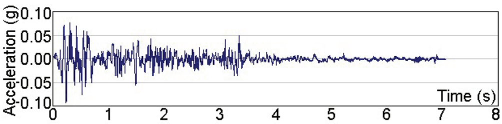

Figure 5. El Centro '40

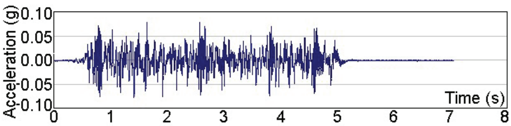

Figure 6. Eurocode 8 artificial earthquake

The results recorded on the shaking table after 53 tests on conventional model and 57 tests on the confined model are comparatively presented below in red and blue colours (Fig.7)

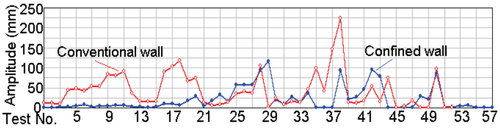

Figure 7. Comparative diagrams of seismic responses

The models displayed essentially different behaviour, the confined model, designed according to a Romanian patent, answered much better to the dynamic excitations. It is worth to be mentioned also that both 3D models reached gradually the ultimate limit state according to *the principle fail-safe.* This result is important when such combined structures are used for critical infrastructures.

CONCLUSIONS

The paper tries to give a holistic idea on the fascinating phenomenon of soil-structure interaction that nowadays became an independent science known under the initials *SSI.* The lessons selected for this brief presentation were inspired by recent doctoral theses appreciated for their practical values. Three final ideas are worth to be also added. The first one refers to the economic effects of the *SSI.* If it is correctly considered by the existing computing programs great benefits can be obtained; benefits not only in investments, but also in the quality of engineering works and their durability. The second idea regards the higher education system. By including *SSI* in the curricula for master degree its value can be much enhanced. Finally, the existing legislation at European level regarding *SSI* should be carefully learn, understood and accordingly applied. The existing case studies confirm that by ignoring *SSI* many avoidable mistakes still occur.

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