Subject Review

SOFT SOILS REINFORCED BY RIGID VERTICAL INCLUSIONS

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ABSTRACT

Reinforcement of soft soils by rigid vertical inclusions is an increasingly used technique over the last few years. The system consists of rigid or semi-rigid vertical inclusions and a granular platform for the loads transfer from the structure to the inclusions. This technique aims to reduce the differential settlements both at ground level as below the structure. Reinforcement by rigid inclusions is mainly used for foundation works for large commercial and industrial platforms, storage tanks, wastewater treatment plants, wind farms, bridges, roads, railway embankments. The subject is one of interest as it proves the recently concerns at international level in research and design; however, most studies deal more with the static behavior and less with the dynamic one.

Keywords: rigid inclusions; granular platform; dynamic loads.

REZUMAT

Ranforsarea terenurilor compresibile prin incluziuni rigide verticale reprezintă o tehnică utilizată din ce în ce mai mult în ultimii ani. Sistemul este alcătuit din incluziuni rigide sau semi-rigide verticale şi o pernă granulară pentru transferul încărcărilor de la structură la incluziuni. Prin această tehnică se urmăreşte reducerea tasărilor diferenţiale de la suprafaţa terenului şi de la baza structurii. Metoda ranforsării prin incluziuni rigide se utilizează cu precădere pentru lucrări de tip fundaţii pentru spaţii comerciale largi şi pentru platforme industriale, rezervoare de stocare, staţii de epurare, eoliene, poduri, ramblee rutiere sau feroviare, ramblee de acces autorutiere. Subiectul este unul de interes, dovadă fiind preocupările din ultimii ani pe plan internaţional la nivel de cercetare si dimensionare, însă majoritatea studiilor s-au referit la partea de comportare statică şi mai puţin la cea dinamică.

Cuvinte-cheie: incluziuni rigide; pernă granulară; încărcări dinamice.

1. INTRODUCTION

The improvement of soft soils by rigid inclusions is used increasingly at international level. This technique allows the foundation on week soils of large civil engineering works such as: road or railway embankments, storage tanks, bridges, wind farms, industrial platforms etc.

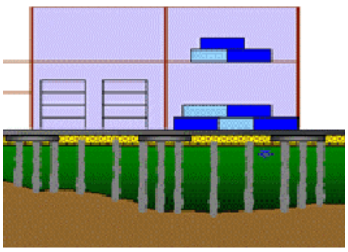

Fig. 1. Foundations for industrial works (Briancon, 2002)

This procedure aims to reinforce compressible soils in order to increase the bearing capacity and to reduce significantly differential settlements, at the ground level, as well as at the structure base, in safe conditions and with respect to economic aspects.

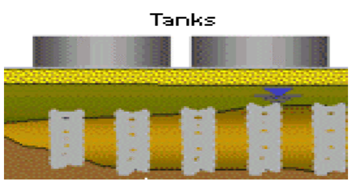

Fig. 2. Foundations for storage tanks (Briancon, 2002)

The transfer of loads is obtained through a system consisting of rigid inclusions and a granular platform, which ensures reduction and uniformity of settlements.

The procedure is not a novelty, considering that geotechnical engineers have been used driven piles as soil reinforcement since the mid-'70s in Scandinavian countries, but, in the last years, the technique was successfully applied using some improvements.

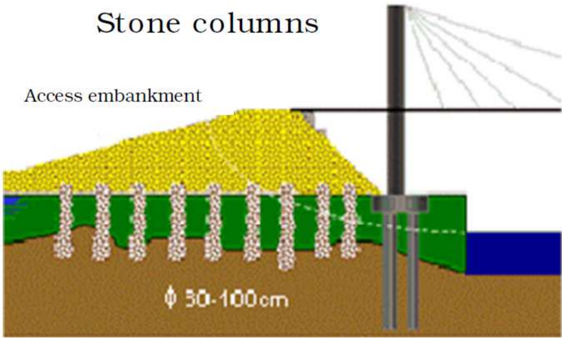

Fig. 3. Access embankment (Briancon, 2002)

The method can be easily adapted to different type of soils and can be used for a wide range of depths ranging from 2.5 to 30 meters. Another advantage is that the procedure can be used for uniform loads. Most of the techniques allow the development of the work without having to discharge and store the soil, which is an advantage both in economic terms, but also in terms of environmental protection.

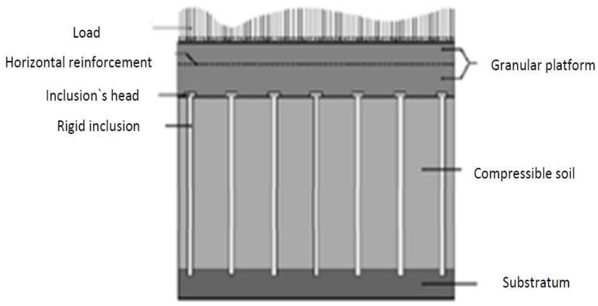

Fig. 4. The principle of soil reinforced by rigid inclusions (Chevalier, 2008)

2. REINFORCEMENT METHODS FOR COMPRESSIBLE SOILS

The rigid inclusions are embedded in the compressible layer and allow the transfer of loads through the development of frictional forces along the inclusions. The granular platform is disposed between the compressible layer and the construction to ensure the transfer of loads to the ends of the inclusions and uniform settlements. The presence of the granular platform makes the difference between this reinforcement method, which uses rigid inclusions, and the traditional method that uses piles, as in this case the inclusions are not linked to the superstructure.

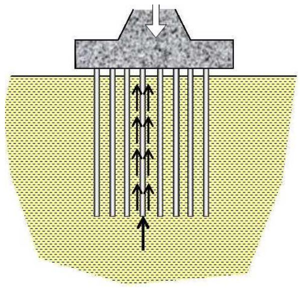

Fig. 5. Simplified scheme of a deep foundation (Hassen, 2006)

At the top of the inclusions, the compressible soil settles more than at the right of the inclusions and induces a negative friction along the inclusion, thus transferring the stresses to the inclusions. At the bottom part, the inclusions are embedded in a layer that is not perfectly rigid, which induces a positive friction; consequently, the maximum stress develops in this area.

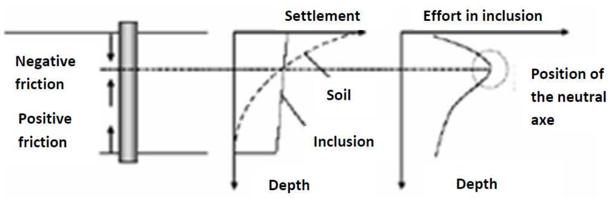

Fig. 6. Friction force along the inclusion (Berthelot et al., 2003)

The various possibilities of reinforcing compressible soils include: foundation on groups of piles, group or network of micropiles.

Depending on their type, inclusions can be precast (driven piles, metallic or made of concrete, with solid section or made of pipes) or cast in place (piles, generally unreinforced - driven or bored piles, continuous flight auger, STARSOL, vibrocompacted concrete columns etc., semi-rigid inclusions, such as controlled modulus columns, and inclusions made by soil mixing with bonding agent-jet grouting, deep-in place mixing, soil-cement columns, lime columns, lime-cement columns).

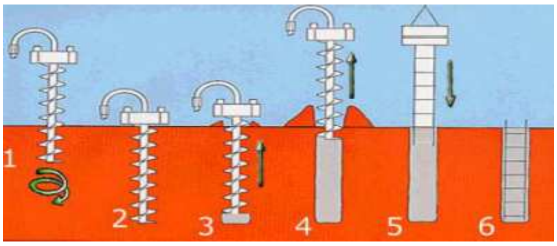

Fig. 7. Schematic diagram for using continuous flight auger (CFA) piles (Briancon, 2002)

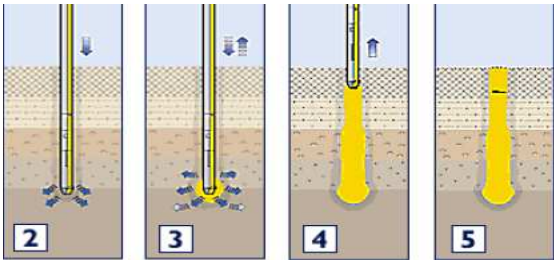

Fig. 8. The principle scheme of using vibro-compacted concrete columns (Briancon, 2002)

The load transfer mechanism that transfers the loads to the inclusions is developed at the granular platform level.

The mattress can be made of treated or untreated granular material that can be improved by addition of binders (cement, lime etc.) or reinforced with horizontal layers of geosynthetic materials that contribute to overtaking the loads by the membrane effect.

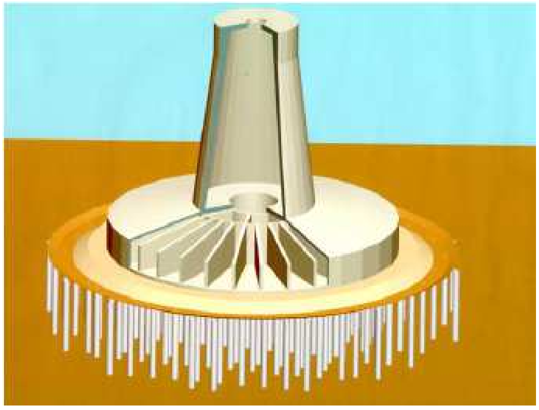

Fig. 9. Soil reinforcement for a pile bridge: Rion - Antirion, Greece (Auvignet, 1999)

Table 1. *Different types of inclusions*

Types of inclusions			Vibrations	Noise	Excavation	E (Mpa)
Precast inclusions	Driven piles		Yes	Yes	No	14000
	Metallic piles		Yes	Yes	No	200000
	Concrete piles		Yes	Yes	No	10000-20000
Cast in place inclusions	Driven or bored piles	Driven piles	Yes	Yes	No	Mortar 2000 7400 Concrete B15: 9000 Concrete B25: 10815
		Dry bored flight auger	No	No	Yes	
		Bored piles	No	No	Yes	
		Continuous flight auger (CFA)	No	No	Yes	
		STARSOL	No	No	Yes	
	Vibrocompacted concrete columns		No	No	Yes	10000
	Controlled modulus columns		No	No	No	500-20000
	Inclusions made by soil mixing with bonding agent	Jet grouting	No	No	No	
		Deep - in place mixing	No	No	No	50-300
		Lime-cement columns	No	No	No	20-200

The transfer granular platform has a very important role as inside it are developing the mechanisms of loads transfer to the inclusions. Due to the use of the granular mattress, the load applies simultaneously on the heads of inclusions and on the compressible soil, which makes the difference between this method and the piled raft method. Pecker and Garnier (1999) and Dobry et al (2003) concluded that the platform is an area of energy dissipation transmitted between structure and rigid components. For the proper functioning of the reinforcement, it should be taken into account that an insufficient thickness of the platform or improper mechanical characteristics may lead to significant differential settlements.

In order to calculate the settlements, the transfer mattress parameters that should be considered are the friction angle (as transfer mechanisms are governed by shear forces) and the deformation modulus corresponding to the load level.

The horizontal reinforcements of the transfer platform are mostly synthetic materials (geotextiles, geogrids), with different roles depending on their position in the mattress. If the geosynthetics are placed directly on the heads of the inclusions, the membrane effect appears, ensuring the load transfer from the compressible soil to the heads of inclusions. If the geosynthetics are placed inside the platform, a configuration that ensures its rigidity, in a similar way to a rigid beam, is achieved.

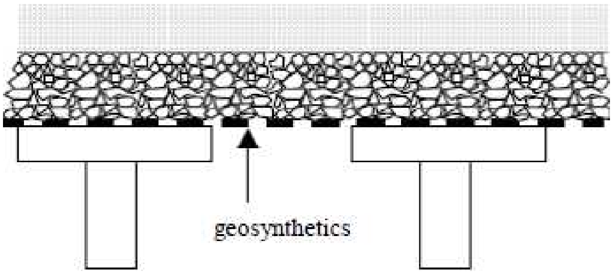

Fig. 10. Layout of horizontal reinforcements directly on the heads of inclusions (Briancon, 2002)

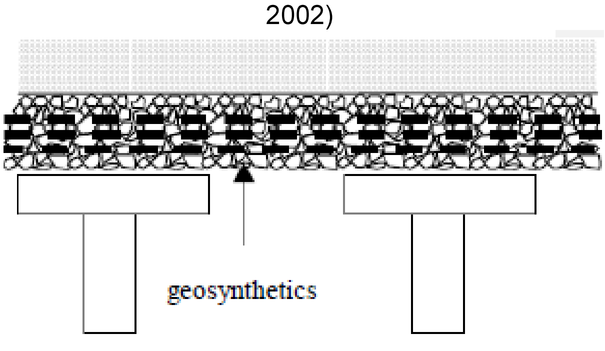

Fig. 11. Layout of horizontal reinforcements inside the granular platform (Briancon, 2002)

Besides the role they have in terms of granular platform, the geosynthetics prevent the lateral displacements of embankments due to the friction between soil and geosynthetics or to the interlocking of aggregates in the geogrid openings. The stiffness increase when using geogrids was demonstrated by German Railways authorities. Seiler (1995) concluded that a 400 mm-thick reinforced ballast layer has the same stiffness as a 600 mm-thick non-reinforced ballast layer.

3. FIELD OF APPLICATION

3.1. General

The most common situations in which this method of improving soils was applied are: embankments, foundations for large commercial or industrial plants, storage tanks and treatment plants.

In the case of road embankments, the use of rigid inclusions ensures the reduction of differential settlements and a shorter construction time, according to Barry et al (1995). Reinforcement by rigid inclusions can solve the differential settlements that may occur in case of enlargement of existing access roads between new and already built zone, which can cause cracking in the road. In case of embankments, the reinforcement is achieved only with rigid inclusions, without using a granular platform.

Foundations of industrial platforms require the presence of a transfer mattress in order to allow the dissipation of energy between the ends of the inclusions and the structure. An essential requirement for different types of foundations is to reduce the differential settlements between foundations and paving.

In the case of storage tanks and treatment plants, as well, the reduction and control of settlements is a prerequisite.

3.2. Applications in Romania

In recent years, several works have been built in Romania using vertical rigid or semi-rigid inclusions as reinforcement for foundation on soft soils of shopping centres, wastewater treatment plants and wind turbines. One of these works refers to soft soils improvement by grouted semi-rigid inclusions for foundation of wind turbines in Dobrogea, in terms of dynamic loads. Required technical parameters were: bearing capacity of reinforced soil 215 kPa for Service Limit State and 310 kPa for Ultimate Limit State, differential settlements should not exceed 3 mm/m and friction angle below foundation $\phi > 27^o$. To ensure ductility and resistance to shear force in dynamic conditions (earthquake), controlled modulus columns (CMC) were reinforced with HA 20 reinforcements over the first 5 meters.

Fig. 12. Improving soft soils for foundation of wind turbines in the Dobrogea region (Menard, 2008)

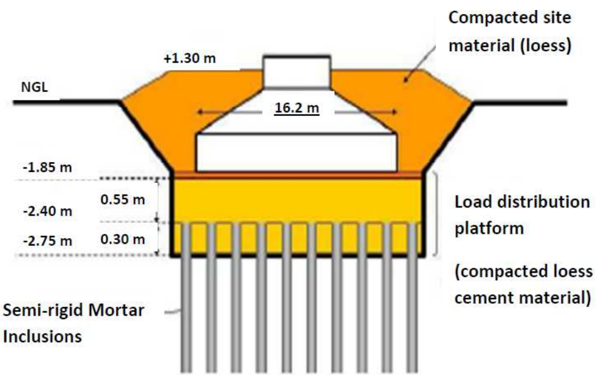

Fig. 13. Section for improving soft soils for foundation of wind turbines in the Dobrogea region (Menard, 2008)

Another important work where rigid inclusions were used was the construction of a wastewater treatment plant in Braila. In this case, the reinforcement consisted of unreinforced concrete piles and a load transfer platform under the whole structure.

3.3. Applications at international level

At international level, methods of soft soils reinforcement by rigid inclusions were developed and used for a long time.

For tower buildings designed in London (Stonebridge Park building, Cavalty Barracks) or in Frankfurt (Commercial Bank, Messeturm), where the ground consists of a thick clay layer, the foundations were made of a group of piles. For the Stonebridge Park in London 301 piles were used, with a diameter of 0,45 m and a length of 13m.

In France, rigid inclusions are used for different types of works. One example is the achievement of a sports centre in western France, close to Loire River, where the soil is very compressible. The solution adopted was to improve the soft soil by rigid inclusions of 300 mm diameter, disposed below the foundations and the base platform. Following a research conducted under the French national project FOREVER, for the Pierre Bridge in Bordeaux (built in 1910) the reinforcement solution that was adopted consisted of micropiles.

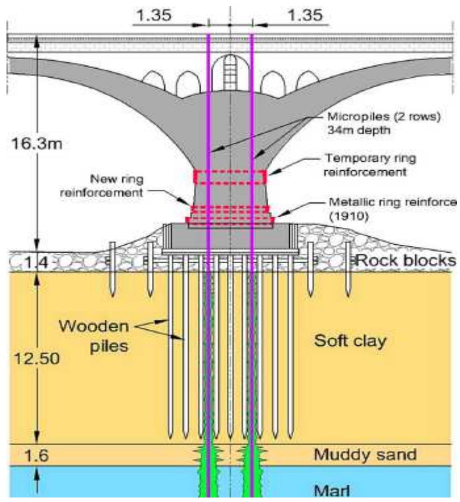

Fig. 14. Vertical section of Pierre Bridge in Bordeaux (Frank, 2006)

Another type of work in which rigid inclusions can be used is slope stabilisation. One example is the stabilization of an unstable slope in order to build a railway embankment in France. In this case, piles of 0.8 m diameter were used, in order to reduce bending efforts and thus to stabilize the slope.

4. BEHAVIOUR OF RIGID INCLUSIONS UNDER SEISMIC LOADING ACTION

4.1. General

Compressible soil reinforcement by rigid inclusions is an important technique when seismic loads are expected, because it allows a better behaviour of the structure – ground system, without damage and risk of stability loss. For seismic loads, this reinforcement system is similar to a base isolation system. The granular platform is an area of energy dissipation between the structure and the rigid inclusions, thus reducing the inertial effect of the superstructure.

In the study of the behaviour of rigid inclusion reinforcements, many factors are involved, which refer to the soil behaviour, to the connections between the inclusions or between the granular platform and the soil, to the load characteristics, as well as different interactions which refer to the whole soil-mattress-inclusions system and the structure.

The seismic motion has spatial and temporal variations during its propagation; these may cause amplification or reduction of the motion.

4.2. Soil behaviour under the seismic loads

The study of soil-structure interaction is performed considering elastic or visco-elastic soil behaviour, although there exists the danger of underestimating the nonlinear ground-structure interaction. For a correct description of the soil behaviour under seismic loads, elasto-plastic constitutive models are required.

According to Gazetas and Mylonakis (1998), in the analysis of the soil-foundation-structure system two types of interactions are involved. The first type is the kinematic interaction, which corresponds to the foundation system response in the absence of the structure.

The second type is the inertial interaction that determines the response of the foundation-structure system for the stresses determined through kinematic analysis. Under the effect of the imposed motion of the foundation, inertial forces are generated in the structure, meaning that additional dynamic efforts are applied to the soil-foundation system.

For a linear soil-foundation-structure system, the dynamic response can be obtained through the superposition of the two interaction types.

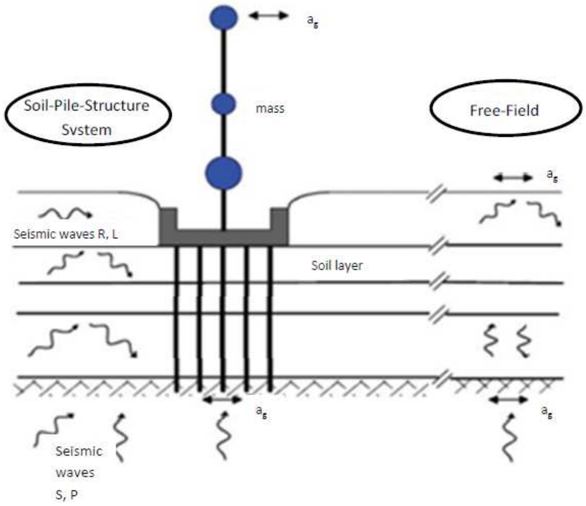

Fig. 15. Soil-structure interaction (Hatem, 2009)

For the soil-structure interaction analysis, a global approach or one based on the superstructure concept can be used. The calculation in the global approach is performed in a single stage, taking into account some important aspects of the soil-structure interaction.

The approach based on the concept of superstructure involves treating the problem in several stages and the calculation in two steps: the determination of foundation displacement by reducing the problem to the kinematic interaction and to the inertial interaction analysis.

4.3. Behaviour of the inclusions under seismic loads

Under seismic loads, rigid inclusion reinforcement behaves as a base isolation system. The granular platform is designed to dissipate the energy between the vertical structure and the rigid inclusions, leading to reduced inertial forces.

Using 2D modelling, Mayoral et al. (2006) studied the dynamic response of a single inclusion. In this study, it was concluded that the use of the granular mattress - inclusions system leads to a reduction by 17% of the ground acceleration, a fact that is mainly due to the transfer mattress.

Using 2D models as well, Rangel Nunez et al. (2006) performed a study by using the finite element method, in order to highlight the behaviour of two sections of soil reinforced by a group of rigid inclusions under seismic loads. Following this analysis, it was shown that for periods of 1.5 s the ordinates of the acceleration spectra increase as the distance between the inclusions is reduced. Spectral accelerations increase at short periods if the inclusions are embedded at the base.

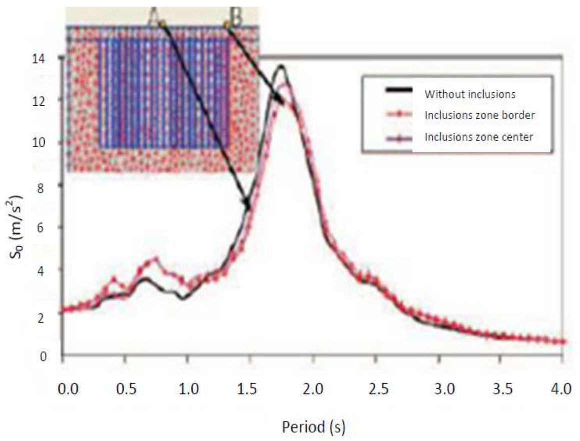

Fig. 16. Acceleration spectra for a soft soil reinforced by a group of inclusions (Rangel Nunez et al, 2006)

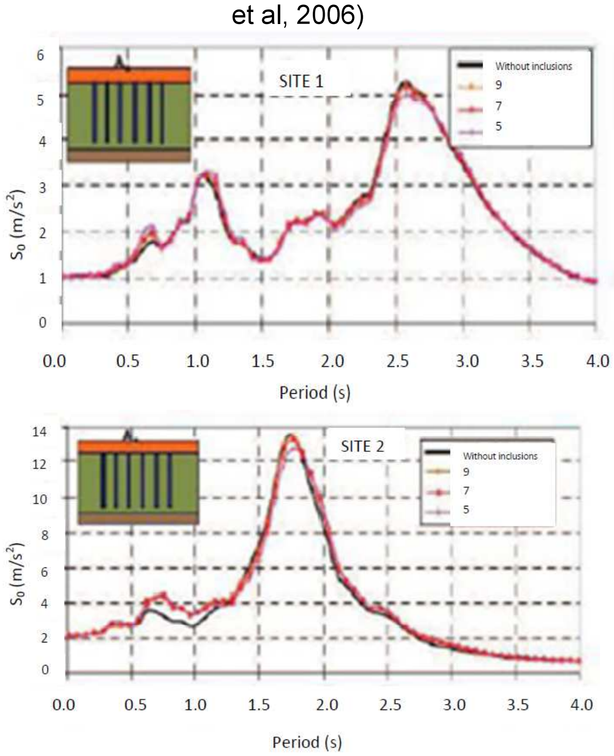

Fig. 17. Acceleration spectra of reinforced soil (Rangel Nunez et al, 2006)

An interesting example of the behaviour of rigid inclusions in seismic areas is the Rion-Antirion bridge in Greece, which is located in a highly seismic zone, for which the maximum ground acceleration is 0.48 g. A 2.8 m-thick gravel layer contributes to energy dissipation through translation and leads to a rupture mode through horizontal translation.

5. CONCLUSIONS

In this paper, several types of rigid inclusions were presented and analyzed, for different types of constitutive materials, manufacturing methods and uses of works.

Regarding the transfer granular platforms it has been shown that there is no universal rule for their dimensioning and that it cannot be stated precisely if it is necessary to add one or more layers of geosynthetics within.

Even if the use of the method is performed without precise calculations, the reinforcement by rigid inclusions technique is increasingly used, especially for works in areas of high seismicity.

The analysis of the behaviour of reinforcements by rigid inclusions under seismic loads highlighted that the presence of the granular mattress has an important role in the transfer of efforts from the structure to the inclusions. Another important aspect refers to the fact that the reduction of the bending moment at the top of the inclusions is due to the fact that these are generally not restrained at the extremities.

For modelling seismic actions, several approaches are used. One of these is that in which stresses from the real ground motion records or obtained from numerical or experimental modelling are expressed in terms of time. Another approach is the one that gives the spectral characteristics of seismic motion.

In practice, the study of the behaviour of rigid inclusions to seismic loads can be reduced to solving the problem of soil-structure interaction, by considering the characteristics of the system consisting of the inclusions and the transfer platform, as well as of the structure characteristics.

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