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INCREASING SEISMIC RESISTANCE BY STRENGTHENING THE FOUNDATION GROUND OF OBJECTS

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Abstract

The foundation soil is the last structural element to which seismic forces are transmitted and is an unavoidable factor of stability, but also a threat to some buildings. Many years of experience in testing and repairing the foundations of buildings in the urban area of Zagreb and Banovina has shown that the soil is degraded in many cases, primarily by secondary influences. Among the most pronounced are the impacts of water resulting from outdated water supply and sewerage infrastructure and climate change causing long droughts and heavy rains. Such soil has poorer geomechanical properties than those according to which the building was designed before construction, and thus does not provide sufficient load-bearing capacity of the building located on it. This problem is even more pronounced during seismic oscillations because it creates an additional load on the foundation soil, resulting in greater displacement of objects, and thus greater risks to people and structures of objects.

In this paper, through mathematical models, but also examples from practice, the impact of earthquakes on buildings with degraded foundation soil, and also the impact on those where foundation soil is strengthened or rehabilitated by the method of expanding resin injection, will be presented. Regardless of the method of improving the foundation soil, each of them contributes to the stability of the building, and thus to seismic resistance; especially in cases where there has been degradation of the foundation soil after its construction.

Keywords: Multipoint, reinforced soil, tests, foundation soil

1. Introduction

The foundation soil represents the area of the soil just below the foundation and is the last construction medium into which all static and dynamic loads of the building are transferred. The foundation is the lowest structural element of the structure which transfers the load of the building to the foundation load-bearing ground and distributes it evenly on a sufficiently large load-bearing surface thus keeping soil compaction within acceptable values and preventing excessive subsidence, tilting or damage. When designing / rehabilitating a building, soil conditions and / or soil properties may not be good enough, i.e., the bearing capacity of the foundation soil under the foundation may be inadequate, and therefore soil improvement measures are required. The action of natural disasters such as earthquakes, due to the induction of large inertial forces and the propagation of seismic waves, consequently reduces the bearing capacity of the foundation soil and the consequent impact on exceeding some boundary conditions of geotechnical structure which can lead to intense damage to the structure. Due to the direct connection between the structure and the ground, the reduction of the load-bearing capacity of the foundation soil (soil degradation) under the foundation, the soil is directly related to the structure and a certain displacement of the foundation will result in cracks, very often in the lower floors of the object itself. Different types of soil during earthquakes conduct differently generated seismic waves of earthquakes and their impact on objects therefore largely depends on the very characteristics of the foundation soil. This indicates the importance of the characteristics of the foundation soil and its role in the stability of structures [1].

Basic soils in our climate are subject to wetting and drying, and thus change in volume and geomechanical characteristics. The soil under the buildings in the city of Zagreb is often degraded by poor drainage systems. Poor foundation soils and local liquefaction are most often caused by poor and outdated water and sewerage infrastructure installations. Poor stormwater drainage and outdated sanitary water drainage systems with vibrations caused by traffic and earthquakes are a huge 'culprit' of poor soil, which then in an earthquake state can not withstand dynamic loads.

2. Foundation soil as an important factor in building damage

Unlike secondary influences that can lead to cracks in "quiet" conditions, earthquakes represent an additional dynamic load that can result in a significantly greater damage to the structure. As seismic waves are transmitted over the foundation soil; first to the foundations and then to the building, the foundation soil is the first "line of defense" and its condition greatly affects the level of damage. At the moment of an earthquake, the foundation sags due to two different mechanisms: one, although momentary, is caused by an increase in forces and moments transmitted to the foundation, where the forces drastically exceed the forces in the static state; second, repeated loading can lead to a loss of soil strength as in the case of soils susceptible to liquefaction. In order to solve the problem with the foundation soil, in addition to the renovation of underground installations, it is necessary to approach soil improvement [2, 3].

The design of buildings takes into account the geotechnical characteristics of the soil on which they will be built, but if this condition of the soil changes and weakens during the use of the building, the level of seismic resistance for which the building is designed will be reduced. Under these conditions, it is necessary to restore the soil strength and bearing capacity. Remediation measures to improve the bearing capacity of the foundations can be divided into two main categories: one is the remediation of the foundation soil, and the other is the remediation of the foundation. Soil remediation methods can greatly improve soil strength and liquefaction resistance at the same time. Given the case of existing buildings, especially in urban environments, the vast majority of available geotechnical methods in these two broad categories are not applicable or severely limited due to excessive noise or vibration generated during construction, size of equipment required or limited usability during construction. Reinforcement of foundation soils by the method of injection of expanding resins has remarkable advantages in terms of such problems in the urban environment and provides a relatively high level of efficiency compared to possible alternatives, especially for existing buildings. An example of positive feedback on the importance of remediation of foundation soil and detection of soil degradation patterns, as well as positive impact during earthquakes, is the remediation project on a 12-apartment building in Haulikova Street built in the early 20th century, rehabilitated before the earthquake. The soil was endangered by an outdated and destroyed sewage system and vibrations near the building, which, when examining the condition of the foundation soil by the DPM method and correlation with the SPT method, established the actual condition of the soil and the position of the endangered part of the foundation soil and its rehabilitation [4, 5].

3. Deep Injections Multipoint

In order to stop the settlement process of buildings or to improve the ground parameters to enable the addition of another floor, it has been developed a low impact technology of local injections of a high-pressure expansion resin into the foundation soil. The Deep Injections-technology is already in action for 25 years now. Its operation steps are relatively simple and do not require invasive excavations or connection systems to the existing and the new foundation structures. The Multipoint-system constitutes the latest improvement of the Deep Injections-technology with further advantages [6].
Deep Injections Multipoint-system is fast, non-invasive and shows immediate results. Small diameter drillings guarantee low vibrations and eliminate the need for any kind of excavation or heavy drilling machines. The injection pipe is pushed in the hole and releases the resin into the soil.

3.1 The injection pipe and the resin

The injection pipe has a diameter of 12 mm and is interrupted by several lateral exit openings for the resin. The diameter of the openings increases with the depth to guarantee a uniform emission of the resin and a coherent improvement of the soil. The resin exits the injection pipe with a pressure high enough to fracture the ground and can therefore also intrude cohesive soils.

GEOPLUS are several fast-expanding polyurethane resins with different expansion pressures ranging from medium to high. Small quantities of the resin are injected precisely underneath the foundation level into the soil volume where the stress state reaches its peak. In order to avoid the material to flow out of this volume, the expansion together with the viscosity increase of the resin has to be very quick. Therefore, after having injected the soil for treatment, the resin immediately starts to expand (Figure 1.). A high expansion pressure of the injection grout is also needed to guarantee a proper compaction of the soil. It has to be way higher than the stress state induced by the overlying structures both to allow a certain expansion rate and to avoid higher material consumption. The expansion process first leads to the compaction of the surrounding soil and then, in case of suitable constructions, also to the lift [7].

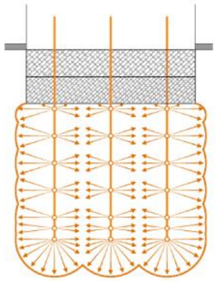

Figure 1. Distribution of exit openings and expansion of the resin

3.2. The injection

To make sure the resin stays in the area to be consolidated, the injection is interrupted several times for a few seconds. In this time the resin expands and compacts the surrounding soil, building a barrier for the following resin of the next interval. All the procedure is monitored by electric receivers lighted by a laser emitter and anchored to the building where the foundation is treated.

3.3. The result

Penetration tests before and after the injection show a significant increase of the required number of blows. During the trials which were made before releasing the new technology, the average increase was 48% for cohesive soils and 75% for granular soils.

4. The project of remediation: Building in Haulikova street, Zagreb

The residential building was built in the 1880s (Figure 2), on four floors with a floor plan measuring 22,0 × 22,0 m, and is located in the center of Zagreb, next to the intensive road traffic road. The building is located on the west side of the sidewalk and on the northern and southern side is paired with other buildings. The building is endangered due to the subsidence of the predominantly eastern part, which is covered with a flat roof of unknown cover, and on the ground floor with a courtyard and old vegetation. During the inspection of the building, significant cracks were noticed along the staircase, which are 1,0 – 5,0 mm wide at the bottom, all the way to the top, where they are up to 10 mm, and along both skylights, more towards the east side approx. 1/5 of edge. The building was built on strip non-reinforced foundations where masonry is a mixture of brick with concrete and stone. The depth of the foundation from the basement is 0,4 m and from the outer surface in the east 1,4 m and from the west 1,8 m, and the width of the foundation is 0,75 m.

a)

b)

Figure 2. View of a residential building a) on the west side and b) east side - subject of reconstruction

4.1. Description of the conditions in the foundation soil

Exploration works were carried out on 15 May 2018. The soil was examined by conducting 8 penetration wells (DPM) and checking the geometry of the foundation at 4 locations . The maximum penetration depth is at well B2 up to a depth of 4,6 m in relation to the level of the surrounding soil. Figure 3 shows the position of the exploration wells.

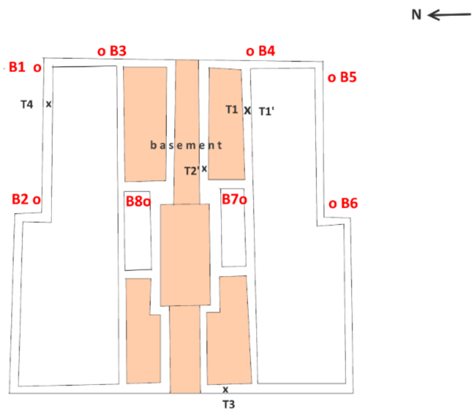

Figure 3. Ground plan position of exploration Wells

Based on the results of the research work, it is concluded that the soil characteristics, just below the foundation structure, in the test areas B1, B2, B3, B4, B5, B6, B7 and B8, was unsatisfactory. These are soft to medium-kneading fine-grained materials, predictably clays or clayey sands. The resistance of the foundation soil is conditioned by the presence of moisture, which oscillates depending on the meteorological conditions of the micro location. The foundation soil layers at the relevant depths do not have satisfactory values of strength parameters. For this reason, it was necessary to improve them. There is a significant impact of rainwater in the depression, which is located in the yard, surrounded by adjoining buildings. A more complete picture of the condition of the foundation soil would be obtained with a more detailed test (SPT or CPT), but given the experience of the world in strengthening the foundation soil with polyurethane mixtures and based on site inspection, soil tests with DPM 30 and correlation with SPT were sufficient to determine the threat zone and to propose soil reinforcement [9].

4.2 The intervention of the remediation in the foundation object

Based on the findings and the examination, it was established that unacceptable subsidence of the foundation structure on its southern, eastern and northern blocks occurred on the subject object by the yard, caused by unfavorable influence of catchment and precipitation waters for many years, and consequently devastation of the foundation soil.

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In order to improve the load-bearing capacity and characteristics of the soil under the strip foundations in the courtyard of the building, and the central foundation inside the building in the basement, remediation of the soil under the foundation is planned based on the remediation project made in June 2018. Since it is a residential building in an urban environment, the rehabilitation solution was considered from several aspects. Expansion resin remediation technology was selected. The advantages of the selected technology are as follows:

• no heavy machinery is used and no construction waste
• injection work is relatively short
• there is no disruption of the daily activities of people in the facility
• reduces the impact of moisture on the foundations and improves the foundation soil
• no environmental pollution

For the mentioned project, grouting was performed on a total length of 50.0 (Figure 4) meters with two-component, polyurethane, expanding resin of the GEOPLUS type by the Deep Injections method. Soil injection was performed up to a depth of 3.0 m below the bottom of the foundation, or about 4.4 m from the surrounding soil with parallel laser monitoring of the movement of the walls of the building. During the injection, the determined displacement values ranged from 0.5 to 2.0 mm upwards. The distance between the injection wells ranged from 0.8 m to 1.2 m, depending on the position of the openings in the walls and the installations found. The works were performed for the most part, a total of 37 wells on the outside and 13 wells inside the building, from the basement position.

a) b)

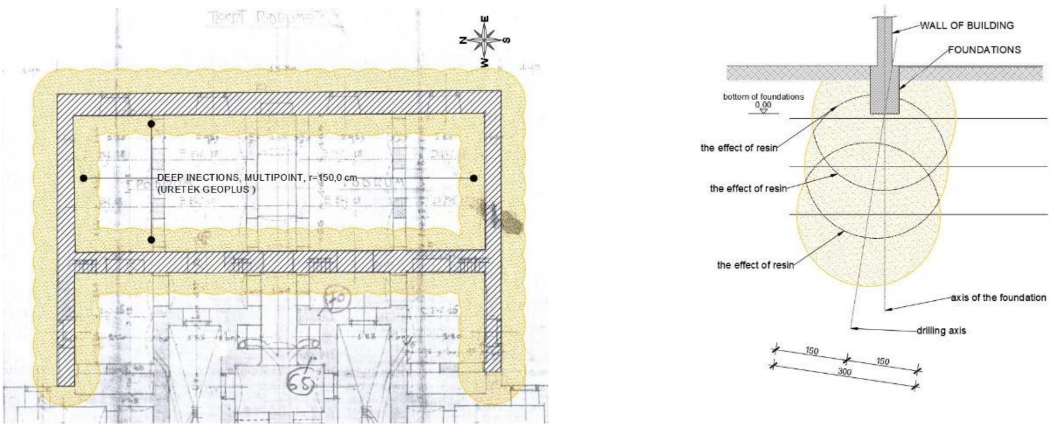


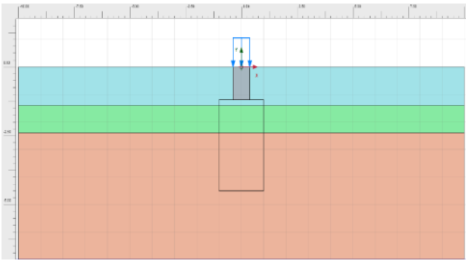
Figure 4. a) Ground plan disposition of the performed reinforcement of the foundation soil b) Characteristic cross-section of the expansion resin spread and injection level

5. Analysis of the results of the numerical model

Geotechnical model of soil, includes, spatial arrangement of layers or zones of soil of similar geological origin and similar mechanical properties, soil parameters (based on correlation DPM and SPT) and the conditions and assumptions under which they represent an acceptable approximation of the natural behavior of the soil in the range of significance for the envisaged construction project and boundary conditions that may affect the chosen geotechnical model. Soil parameters obtained based on correlation are as follows (Stroud & Butler (1975)) [8]:

1. Layer – CL from 0,0 m to 1,4 m (γ = 20 kN / m3; c = 20 kPa; φ = 26; Ms = 6 MPa),
2. Layer – CI from 1,4 m to 2,4 m (γ = 19 kN / m3; c = 18 kPa; φ = 25; Ms = 3,5 MPa),
3. Layer – CH from 2,4 m to 7,0 m (γ = 20 kN / m3; c = 30 kPa; φ = 20; Ms = 11 MPa),

The settlement calculation was performed using Plaxis 2D and 3D ver. 2017 (finite element method). The soil is modeled using a nonlinear hardening model of the soil. The distances of the boundaries of the computational model from the place of the largest stress changes were selected according to the usual rules of numerical modeling. Horizontal displacements are prevented in the nodes of the vertical boundaries, while vertical and horizontal displacements are prevented in the nodes of the lower boundary.


a)

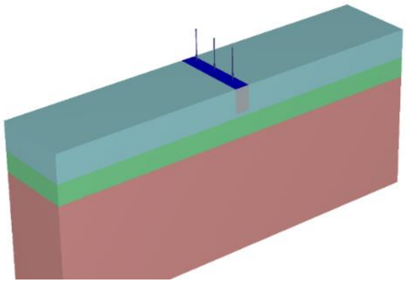
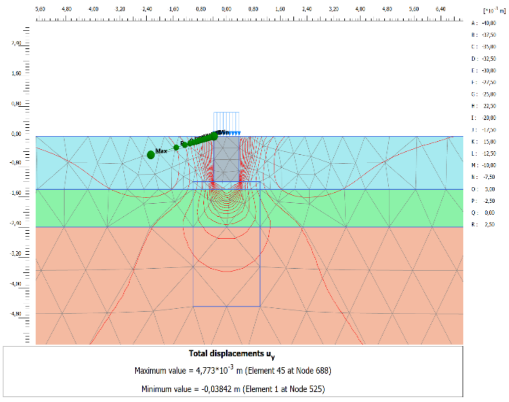

b)

Figure 5. a) 2D model b) 3D model

The estimated subsidence of the foundation of the building before injection from the weight of the building (156 kN / m2) is 3,84 cm (Figure 6, a), while with an additional load of 30% (200 kN / m2) is 6,39 cm, which is an additional settlement of 2,55 cm. According to the analysis of the reinforcement of the foundation soil multipoint technology and the application of an additional load of 200 kN / m2, the settlement is 4,34 cm (Figure 6, b), which is an additional settlement of 0,5 cm compared to the settlement from the building without any additional load and thus the ratio of the effect of improvement is 5.1 times higher.

a) b)



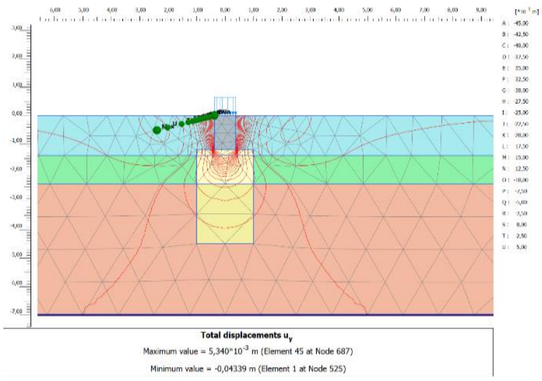


Figure 6. a) Subsidence of the object from the weight of the object itself before injection b) subsidence of the object at additional load after injection

6. Comparative penetration test results before and after the injection

After strengthening the foundation soil, the control test is approached with the DPM 30 device, and the obtained results of soil testing before and after injection (according to the obtained number of strokes) are compared to obtain data on increasing the compaction of the foundation soil and the success of injection which automatically determines the depth of soil reinforcement.. In Table 1 are given the results of the penetrometer test using DPM-30 and correlation with the SPT method for a drillhole B1 before injection and the results of the initial test for determination of the initial state of the foundation soil. Also, in this table are given the results obtained after grouting and soil improvement by using expansion.

Table 1 - Comparative results of the B1 penetrometer test before and after injection and correlation with SPT

Depth (m)			*Test B1 i B1'*			
	number of strokes before injection DPM 30	**number of strokes before injection SPT**	**Dynamic resistance (kg/cm^2)**	**number of strokes after injection DPM 30**	**number of strokes after injection SPT**	**Dynamic resistance (kg/cm^2)**
0,10						
0,20	12	9	42,80	-		
0,30	12	9	42,80	-		
0,40	21	16	74,90	-		
0,50	15	12	53,50	-		
0,60	14	11	49,93	-		
0,70	10	8	35,67	-		
0,80	9	7	32,10	-		
0,90	10	8	35,67	-		
1,00	9	7	32,10	-		
1,10	12	9	38,67	-		
1,20	12	9	38,67	-		
1,30	11	8	35,45	Bottom of foundations		
1,40	10	8	32,22	21	16	67,67
1,50	7	5	22,56	21	16	67,67
1,60	5	4	16,11	20	15	64,45
1,70	5	4	16,11	20	15	64,45
1,80	5	4	16,11	19	15	61,23
1,90	6	5	19,33	20	15	64,45
2,00	6	5	19,33	21	16	67,67
2,10	6	5	17,62	26	20	76,36
2,20	5	4	14,69	23	18	67,55
2,30	7	5	20,56	16	12	46,99
2,40	5	4	14,69	22	17	64,62
2,50	22	17	64,62	21	16	61,68
2,60	25	19	73,43	21	16	61,68
2,70	20	15	58,74	21	16	61,68
2,80	22	17	64,62	17	13	49,93
2,90	20	15	58,74	17	13	49,93
3,00	22	17	64,62	20	15	58,74
3,10	20	15	54,00	23	18	67,55
3,20	18	14	48,60	22	17	64,62
3,30	22	17	59,40	23	18	67,55
3,40	22	17	59,40	20	15	58,74
3,50	22	17	59,40	23	18	67,55
3,60	20	15	54,00	27	21	79,30
3,70	15	12	40,50	24	18	70,49
3,80	16	12	43,20	22	17	64,62
3,90	19	15	51,30	31	24	91,05

Based on the results shown in Table 2 above, it can be seen that after the remediation of the foundation soil by the injection of explosive resin, the number of stroks obtained by testing with DPM-30, and thus dynamic resistance, is higher than the results obtained before the remediation process. This leads to the conclusion that the bearing capacity of the soil after grouting is higher, which proves us how successful the rehabilitation of the foundation soil was. It should also be noted that, following the earthquake which hit Zagreb in March 2020, it was determined that the building survived it with only a few small cracks without any major damage or endangering stability.

7. Conclusion

Expansive polymer injection improves soil resistance through two different modes, depending on the soil type and injection method: first, in the parts of the soil where the resin is impregnated, the void in the soil is filled with expansive resin and a chemical bond is given between the solid particles that make up the soil; secondly, due to the expansive character of the resin, the injected soil increases in volume, exerting significant pressures on the environment thus resulting in an increase in effective stress and a reduction in voids (compaction) in the soil mass strengthening foundation soils against earthquake-related damage. Geostatic calculation and settlement control before strengthening the foundation soil when applying additional load, the settlement is higher by only 2,55 cm, which is not so big, but given the condition of the building structure and the appearance of cracks, the need for urgent intervention of soil reinforcement was higher. Geostatic analysis and damage to the building in Haulikova Street before the March 2020 earthquake led to the conclusion that the building was threatened by soil stability and degradation, which led to soil reinforcement to increase static and dynamic (earthquake) resistance. The success of this was further confirmed by monitoring the movement on the building after the intervention, whereby in both periods (from the intervention to the earthquake and after the earthquake) no significant changes were recorded. Experiences in the application of polyurethane resin injection technology in the city of Zagreb and its surroundings after the earthquake have shown through monitoring similar or equal results of the success of soil reinforcement.

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