IOP Conf. Series: Materials Science and Engineering **245** (2017) 022055 doi:10.1088/1757-899X/245/2/022055

Application of Soil Nailing Technique for Protection and Preservation Historical Buildings

Marek Kulczykowski[1], Jarosław Przewłócki[2], Bogusława Konarzewska[1]

[1] Institute of Hydro-Engineering, Polish Academy of Sciences, ul. Kościerska 7, 80-328 Gdańsk, Poland,

[2] Gdańsk University of Technology, Faculty of Architecture, Narutowicza 11/12, 80-233 Gdańsk, Poland,

architektka@wp.pl

Abstract. Soil nailing is one of the recent *in situ* techniques used for soil improvement and in stabilizing slopes. The process of soil nailing consists of reinforcing the natural ground with relatively small steel bars or metal rods, grouted in the pre-drilled holes. This method has a wide range of applications for stabilizing deep excavations and steep slopes. Soil nailing has recently become a very common method of slope stabilisation especially where situated beneath or adjacent to historical buildings. Stabilisation by nails drilled into existing masonry structures such as failing retaining walls abutments, provide long term stability without demolition and rebuilding costs. Two cases of soil nailing technology aimed at stabilising slopes beneath old buildings in Poland are presented in this paper. The first concerns application of this technology to repair a retaining wall supporting the base of the dam at the historic hydroelectric power plant in Rutki. The second regards a concept of improving the slope of the Castle Hill in Sandomierz. An analysis of the slope stability for the latter case, using stabilisation technique with the piling system and soil nailing was performed. Some advantages of soil nailing especially for protection of historical buildings, are also underlined. And, the main results of an economic comparison analysis are additionally presented.

1. Introduction

Many old monuments rest upon raft foundations or stepped foundations. Some aspects of the history of foundation engineering with a particular regard to its development, applied techniques and materials are given by Przewłócki et al. [1]. Several examples of historical foundations as well as past and contemporary preservation techniques are also presented in this paper. Construction activity close to historical structures is a tricky issue due to several restrictions. The problem becomes especially difficult when buildings are set on slopes or embankments. In such cases their structures should be adequately protected usually by strengthening their foundations or underlying subsoil. There are several methods of soil stabilisations used in slope protection. Proper reinforced soil techniques appear to meet most of these restrictions in reference to historical objects.

The concept of reinforced soil is relatively old. People in ancient cultures used sticks and branches for reinforcing mud houses and religious objects. However, the origin of soil nailing developed during the last century in the early 1960s. At the same time steel reinforcement and shotcrete have been used for the stabilisation of slopes. Soil nailing has recently become a very common method of slope stabilisation especially where it is situated beneath or adjacent to historical buildings.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

Reinforced soil can be considered as any massive ground supporting system, usually wall or slope, in which reinforcing elements (inclusions) are placed in the soil mass to improve its mechanical properties. Inclusions can be of various shapes and made from different materials. Nailing is a technique where natural soil is reinforced by the insertion of slender tension-carrying elements called soil nails. The tensile forces are developed in the soil nails by the frictional interaction between the soil nails and the ground. Facing is a component of the reinforced soil system used to prevent the soil from ravelling out between the rows of reinforcement. Common facings include pre-cast concrete panels, metal sheets, shotcrete, geosynthetics, etc.

Soil nailing technology which aims to stabilise slopes supporting or adjacent to old buildings has been increasingly used in practice and widely described in the literature. Some recommendations and examples of this method are given in books written by Smoltczyk [2] and Phear et al. [3]. Gannon [4] describes masonry buildings in Scotland and Walker, et al [5] deal with dry-stone retaining wall construction in Britain and France stabilised by soil nailing. Mittal and Sweta [6] used this method as it results in negligible detrimental effect to historical buildings in close neighbourhoods. Besides they have prooven, similarly to Phear et al. [3] that nailed construction costs are much lower than other conventional underground construction techniques.

In this paper, an example of the repairing of a dam in the historic hydroelectric power plant in Rutki, near the old Polish city Gdańsk (figure 1), by using the soil nailing technique is presented. On the other hand the concept of application of this technology to stabilize and improve the slope of the Castle Hill in Sandomierz, as an alternative method to the classical piling system used in this case, is proposed. The damage to the castle caused by slope instability is described. The technique using concrete raked piles for ground improvement, applied to protect the castle, is given. The results of a slope stability analysis before stabilisation and for stabilisation using both the piling system and soil nailing are presented. For the both techniqus an analysis concerning economics was performed.

Figure 1 Location of Rutki and Sandomierz on the map of Poland

2. Soil nailing technology

Soil nailing is an *in situ* soil reinforcement technique that has been used for the last three decades for stabilising slopes and retaining excavations [7], [8]. The soil nailing process includes the installation of nails into the excavated cut or in the slope either by driving and grouting in pre-drilled holes. The construction sequence for such excavations is presented in figure 2a.

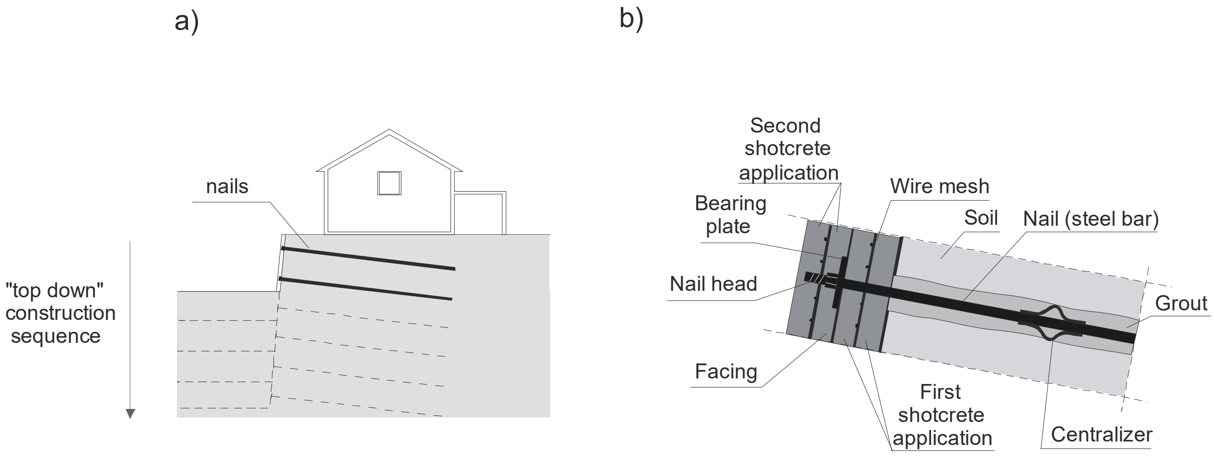

Figure 2 Soil nailing: a) construction sequence, b) typical soil nail detail

Soil nailing is performed by staged excavations from "the top down". It consists of several steps which include subsequent excavating of soil layers, covering exposed surfaces with shotcrete, nailing with steel inclusions and grouting. Nails are generally high-strength steel bars (up to 50 mm in diameter) placed in the boreholes with vertical and horizontal spacing varying typically from 1 to 3 m. The nails are then cement grouted by gravity or under low pressure in order to ensure the bond between the ground and reinforcement. The zone of reinforced soil performs as a homogeneous and resistant unit. It supports the unreinforced ground behind much as a conventional gravity retaining wall.

Shotcrete facing is often used in soil nailing wall construction. The main functions of the facing are to ensure the stability of the ground between the reinforcement layers, and to protect the soil from surface erosion. The facing is generally reinforced with a welded wire mesh and its thickness is obtained by application of successive layers of shotcrete (figure 2b).

Soil nails are relatively simple and inexpensive to install, and there is only a little disturbance to the surrounding ground. This technology is flexible, as both structural elements (i.e. inclusions and facing) and installation techniques can be easy adopted to provide the most appropriate solution for specific site conditions. Therefore this method has also been used successfully in remedial construction, for example for repair or restoration of masonry gravity retaining walls.

3. Application of soil nailing technology for strengthening the dam under a hydroelectric power station

The historical hydroelectric power plant in Rutki was built in 1910 on the Radunia river, 20 km west of Gdańsk. The water flow of this river, having an alpine character with a fast current, is blocked by a 12-meter-high soil dam. The toe of this dam is supported by a 5-meter-high concrete retaining wall (figure 3a). In 1988, numerous cracks were observed in the stone facing of this construction. The immediate repair of the wall was needed to prevent failure caused by long decay of the structure. The application of soil nailing technology repaired this old retaining wall and strengthened the base of the dam without its demolition. The method developed in Institute of Hydro-Engineering Polish Academy of Sciences in Gdańsk (IBW PAN) [9] was used to design of this soil nailed retaining structure.

In the first stage of wall restoration the stone facing was dismantled, then a layer of light steel mesh was fixed to the wall and a 70 mm thickness of concrete was sprayed. Next, the nail holes were drilled through the structure in vertical and horizontal spacing's of 1.3 m. Then the high yield steel rods, 16 mm in diameter and 5 meters long, were placed and grouted into these boreholes. Finally, a stone facing was applied as a finish to the stabilized wall (figure 3b).

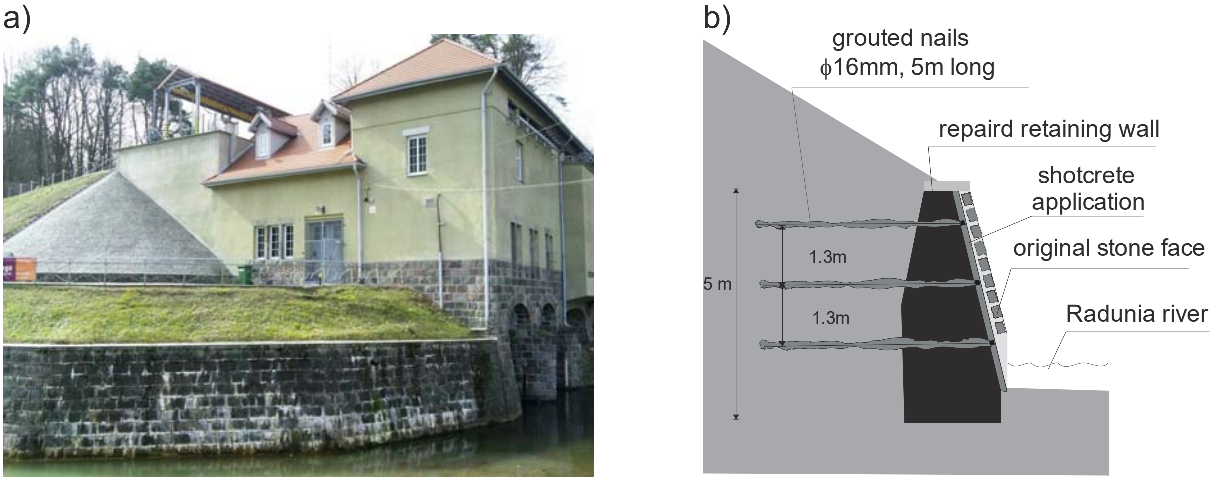

Figure 3 Hydroelectric power plant in Rutki: a) retaining wall supporting the dam and the power plant building, b) stabilisation of old gravity wall using soil nailing

4. Sandomierz Castle - the causes of damage and applied repair technique

Sandomierz is one of oldest and historically most important cities in Poland, situated on the Vistula River, in the south-eastern part of the country (see figure 1). The city, with over 120 antiquated buildings, is located on seven hills cut through by deep ravines.

The Castle in Sandomierz is set on a hill on a slope leading down to the Vistula River. It was erected on the site of a former fortress from the 10th century. This royal-founded brick and stone building was built beginning in the 14th century. In 1525 it was transformed into a Renaissance residence. The castle was blown up by the Swedish army in 1656. Only the western wing was preserved and was used as a prison from 1821. The building was rebuilt in the years 1960-1986. Now it is the seat of the Sandomierz Regional Museum [10].

At present the castle is a rectangular building having a dimension of 63 meters in long and 15 meters wide with a courtyard on the eastern side. Two of the castle's exterior towers are located on the north-west and southwest corners of the main building (figure 4).

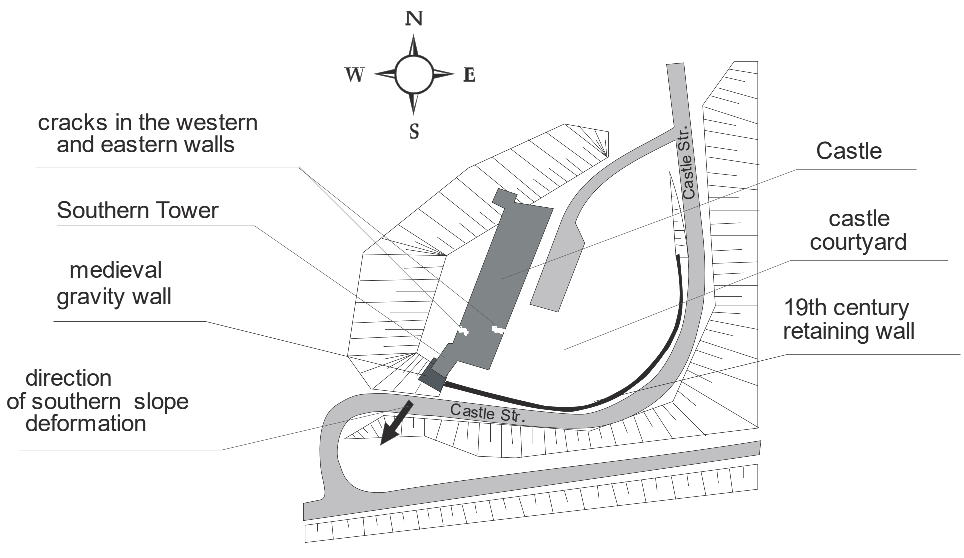

Figure 4 Site plan of Castle Hill

The Southern Tower is situated on the edge of a very steep slope, in the immediate vicinity supported by an 11-meter-high medieval masonry gravity wall. The courtyard's area is also surrounded on the east and south sides by a curved 19th century retaining wall (figures 4, 5).

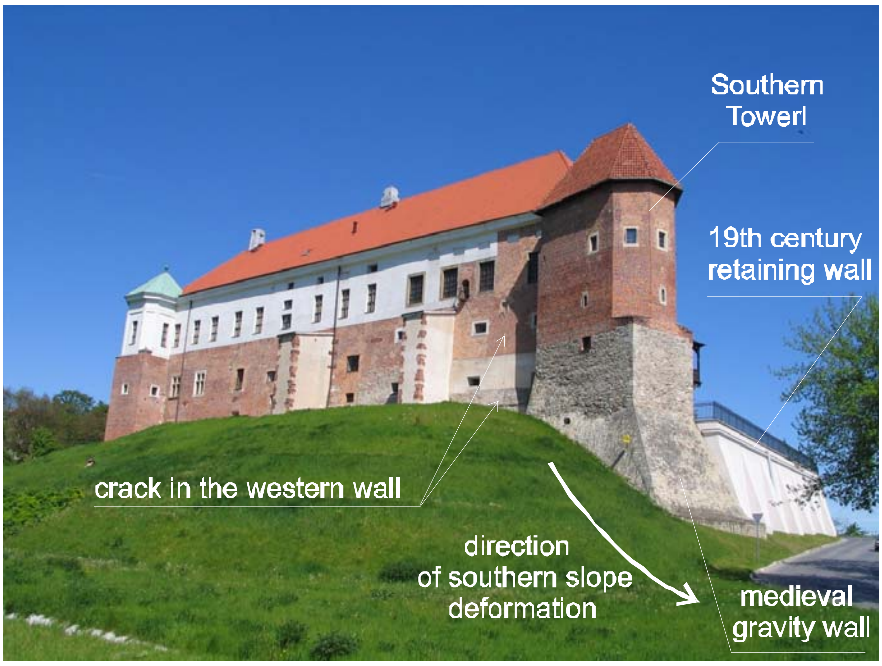

Figure 5 Castle Hill – south-west side view

Lithologically, loesses overlying sands and shales form the area of Castle Hill. The castle rests upon a 9 m thick loess layer, underlain by 7 m thick sand layer. The lowest layer consists of quartz-mica and clayey shales, which are adjacent to generally water-impermeable cohesive rocks. Below the southern slope of Castle Hill the loess and sand layers dip toward the Vistula River (figure 6).

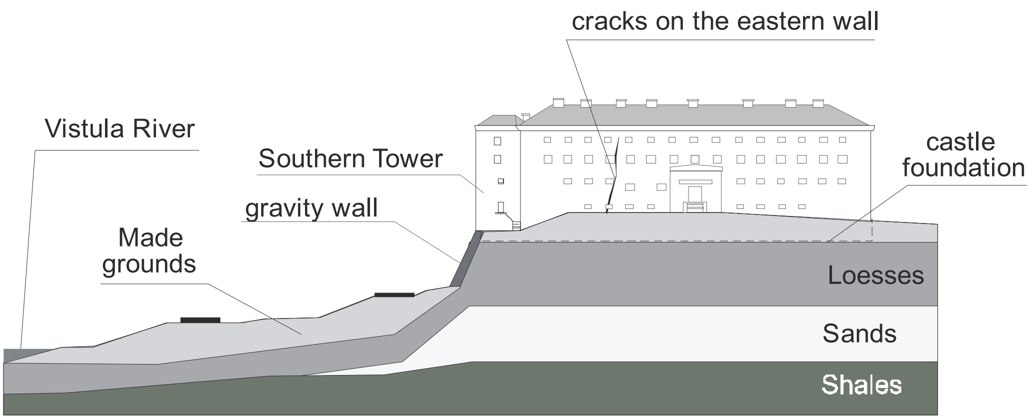

Figure 6 Castle Hill- east side view and geological formation

In the 1990s, the numerous long vertical cracks in the castle walls appeared (figures 4-6). This damage was caused by potential slope failure due to ground deformation in the southern part of Castle Hill. This seriously affected the stability of the Southern Tower, the oldest preserved part of the castle. The loss of bearing capacity of the subsoil was caused by a rise in soil moisture of Castle Hill and the traffic vibration from the nearby neighbourhood.

Deformation measurements indicated the absolute necessity of soil stabilisation in the southern slope of the hill. Therefore the classical ground stabilisation technique using reinforced concrete raked piles was applied in the area around the base of the tower. Bored reinforced concrete piles 0.67 m in diameter and of an average length of 11 m were installed at a 15-degree inclination with 3-meter spacing. Cast-in-place reinforced concrete pile caps, joining pile heads together, had a dimension of 14 meters in length, 1.5 meters wide and 1.6 meters high. The location of the piling zone and applied piling system is presented in figure 7.

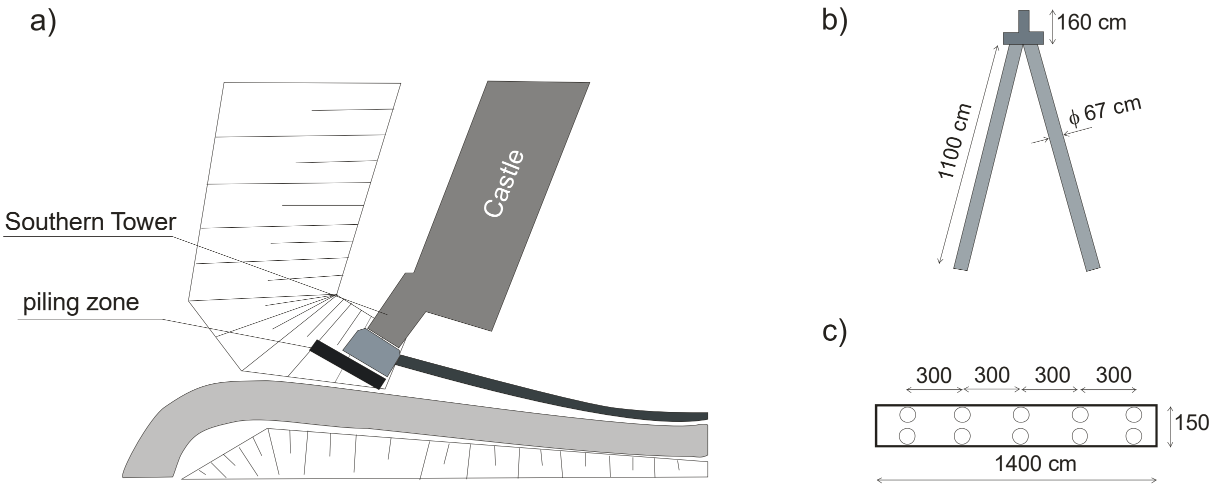

Figure 7 Piling at Castle Hill: a) localization of the piling zone, b) concrete raked piles, c) piling system

5. Soil nailing as alternative solution of slope stabilisation

Soil nails can be used to stabilize and strengthen failing or unstable slopes or structures. This system has equal facility in remedial projects. Soil nails can be installed directly through the faces of old masonry walls and be fastened and hidden inside these structures without demolition. Therefore soil nailing is convenient for repairing or restoring historical construction.

Thus, soil nailing technology was proposed to stabilize and improve the slope of Castle Hill, as an alternative method to the classical piling system applied in Sandomierz. The method developed in IBW PAN [9, 11] was used for the design of this soil nailed retaining structure. This procedure is based on a limit analysis method while reinforced soil is treated as a composite material. The internal and global stability of the soil nail structure, its maximum tensile force distribution and ultimate pull-out resistance of the soil nails were analysed. Based on the results of these analyses, the wall cross- sections, including the number of nails, vertical and horizontal nail spacing, and nail inclination and length were established.

According to the proposed concept, nails were installed through the medieval masonry gravity wall supported by a steep slope in the immediate vicinity of the Southern Tower. The face of this retaining structure having a dimension of 12 meters long and 11 meters high, is inclined at 60 degree from horizontal. A geotechnical exploration revealed a uniform layer of loess behind and below the gravity wall. Based on results from the geotechnical exploration and laboratory testing, the following main geotechnical parameters were selected for design: soil unit weight, effective friction angle and cohesion. The permanent load acting on the wall included the weight of the soil behind the wall and the loads from the structures situated above the wall i.e. the tower and castle.

Based on the results of design calculations the reinforcement material and soil-nail configuration were established. The reinforcement material is of 32 mm diameter high-yield bar with a threaded end (steel S355 with a specified minimum tensile strength of 470 N/mm^2). Centralised, 20 meter long bars were inserted and grouted in the soil and within the wall at an inclination 10^o down. Soil nails are installed in a grid pattern, at horizontal nail spacing of 1.2 m and vertical spacing of 1.5 m. This vertical spacing resulted in seven rows of soil nails (figure 8a).

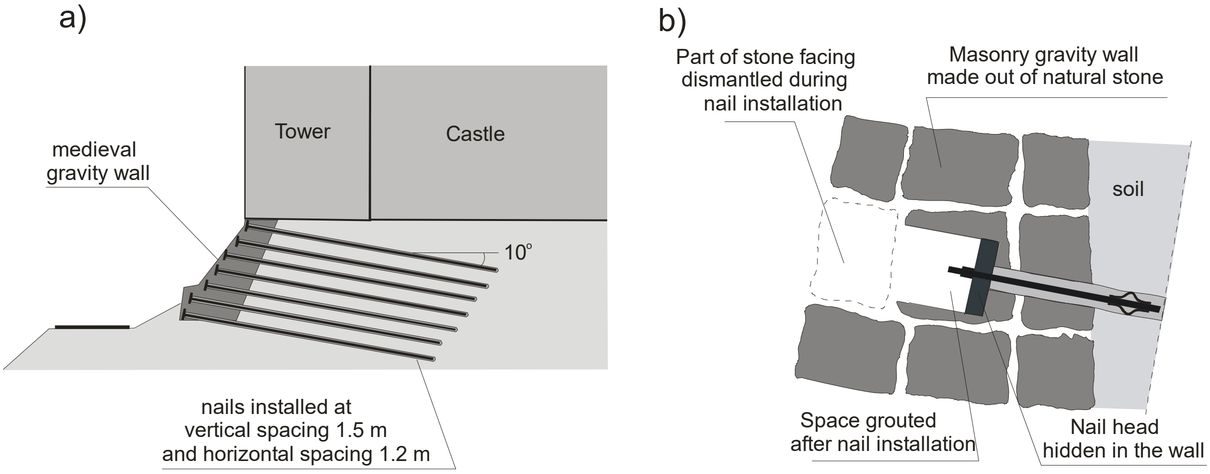

Figure 8 Alternative approach of slope stabilisation using soil nailing technique: a) cross-section of nailing zone, b) solution for fastening the nail head within the masonry

The nails were drilled through the wall and grouted into the soil beyond. The heads of the nails were fastened and hidden within the wall. The stones removed from the facing during the nails installation were put back into their previous places, so the original look of historical monument was preserved (figure 8b).

6. Stability analysis

To compare and to assess the effectiveness of both stabilisation techniques described above, a slope stability analysis, based on two-dimensional, limit-equilibrium method was performed. In this method the forces or moments resisting movement of the mass with those that can cause unstable motion are compared. The rotational movement on potential slip surfaces below the soil mass and the circular shape of slip surfaces are considered. The output of the analysis is a factor of safety (F_s), defined as the ratio of total resisting forces to total driving forces along a certain slip line. The analyses also provide a critical slip surface correspondent to the lowest F_S value. If the value of the safety factor is less than 1.0, the slope is unstable. For static conditions of permanent structures the minimum safety factor should be $F_S = 1.5$.

In the analysis performed three cases of stability of Castle Hill’s southern slope are considered: slope before stabilization, slope stabilized with a piling system, and with soil nailing. In the last two cases internal and overall stability are checked. Internal stability analysis includes slip surfaces intersecting with some or all of the piles or soil nails, while in the overall stability analysis the slip surfaces must be considered to extend behind the soil reinforcement, hence disregarding any contribution to stability from the piles or nails.

The results of the slope stability analysis are presented in figure 9. Figure 9a shows the results of the analysis performed in the case of the unreinforced slope. In this case the circular slip surface corresponding to the lowest F_S value starts nearby the cracking zone of the castle wall. The minimum safety factor F_S is less than 1.0, which confirms slope instability.

The results of the stability analysis of the slope protected with a piling system are given in Figure 9b. In this case the internal and overall stability are analysed. The circular slip surface obtained for internal stability analysis starts also nearby the cracking zone. In this case the factor of safety is significantly above the minimum value. As to overall stability the slip surface goes deeper, below the pile bases and the corresponding factor of safety becomes smaller, but is above the minimum value.

IOP Conf. Series: Materials Science and Engineering **245** (2017) 022055 doi:10.1088/1757-899X/245/2/022055

The results obtained for the proposed soil nailing system, shown in Figure 9c are nearly similar to those from the previous analyses. In this case the circular slip surface obtained for internal stability analysis also starts nearby the cracking zone, and in overall stability the slip surface goes deeper, just below the soil nailing zone. The safety factors resulting from internal and overall stability are almost identical and are also above the minimum value.

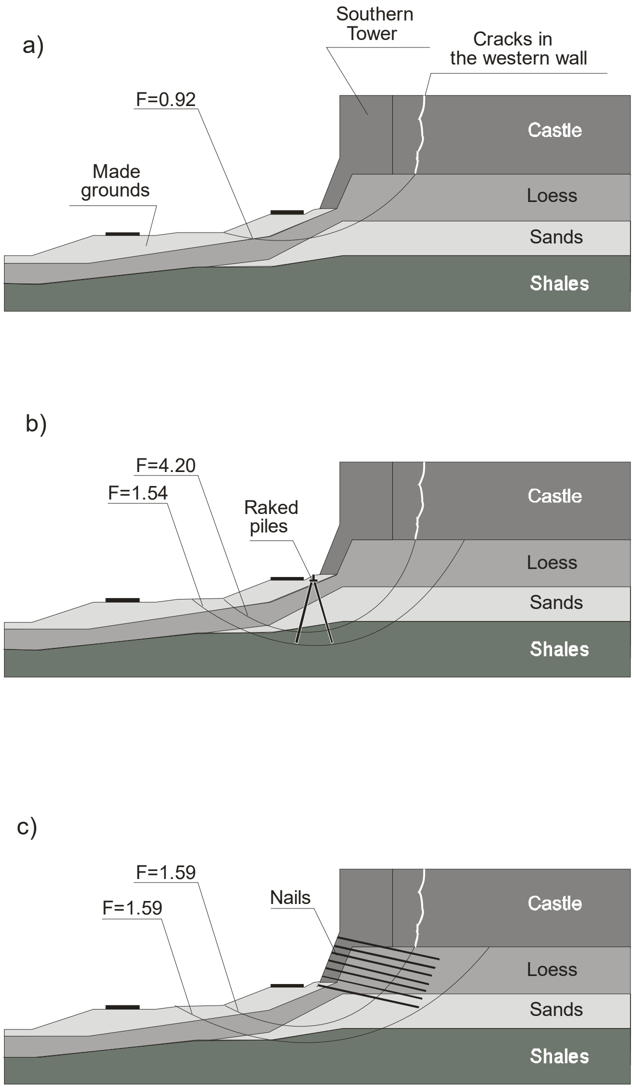

Figure 9 Stability analysis: a) slope stability before stabilisation, b) slope stabilized with piling system, c) slope stabilized with nailing system

The presented results confirm the correctness of the analysed slope stabilisation systems for the southern slope of Castle Hill, both in the case of piling and for soil nailing. Stability analyses indicate that these constructions are safe and produce adequate factors of safety.

On the other hand, the economic analysis performed in the case of Castle Hill in Sandomierz, for the applied classical technique of ground improvement using either concrete raked piles or soil nailing, proved a cost reduction over 30% in the latter case. This indicates the high competitiveness of this method.

IOP Conf. Series: Materials Science and Engineering **245** (2017) 022055 doi:10.1088/1757-899X/245/2/022055

7. Conclusions

Reinforced soil allows existing historical structures to be stabilised without rebuilding, and contributes to cost saving and maintaining serviceability. An economic analysis performed on Castle Hill in Sandomierz as well as on other soil nailing structures, indicates that this technology leads to cost reductions of about 30% in relation to classical methods. Soil nailing is presently commonly used to stabilize retaining walls in the restoration of old structures and buildings that are located in various soil conditions. It is one of the most effective solutions for slope stabilising methods. It is also worth to mention the simplicity, reliability, lack of vibration and low noise levels during the work of nailing. What is worth emphasizing when applying this method, is that architectural features in most cases remain unaffected by soil nails, as they can be sited to pass around or between obstacles. Soil nailing applied to existing masonry structures such as failing retaining walls abutments provide long term stability without minus demolition and rebuilding costs. This technology, as the stability analysis has shown, ensures similar global factor of safety in comparison to applied one, as in the case of Castle Hill in Sandomierz. The analysis presented in this paper as well as in some other cases known to the authors, clearly shows that soil nailing should be considered as an attractive, alternative solution for stabilizing slopes in order to protect historical buildings, because of both practical issues and the actual savings it provides.

Acknowledgment

The he authors would like to thank the Regional Museum in Sandomierz for providing valuable information, data and photographs.

References

[1] J. Przewłócki, I. Dardzińska, J. Świniański, “Review of historical buildings’ foundations”. Geotechnique, Vol. 55, No. 5, 363-372, 2005.
[2] U. Smoltczyk, “Geotechnical Engineering Handbook”, *Ernst and Sohn. A Wiley Company,* 2003.
[3] A. Phear, C. Dew, B. Ozsoy, N.J. Wharmby, J. Judge, A.D. Barley, “Soil nailing – Best practice guidance”, CIRIA, London, 2015.
[4] J. A. Gannon, “Masonry retaining wall reconstruction and rock face stabilisation using soil nails, masonry and dowels”, Engineering Geology, Special Publications, Vol. 10, 345-354, 1995.
[5] P.J. Walker, J.C. Morel, B. Villemus, “Outline of dry-stone retaining wall construction in Britain and France”, 12th International Brick/Block Masonry Conference, Madrit-Spain, 1909-1927, 2000.
[6] S. Mittal, N. Sweta, “Underground basement construction adjoining historical monument by soil nailing – a case study”, Proceedings of Indian Geotechnical Conference, Kochi, 1058-1060, 2011.
[7] D.A. Bruce, R.A. Jewell, “Soil nailing: application and practice - part 1, Ground Engineering, 19:8, pp. 10-15, 1986
[8] I. Juran, “Nailed-Soil retaining Structures: Design and practice”, Transportation Research Record 1119, pp.139-150, 1987
[9] D. Leśniewska, M. Kulczykowski, „Reinforced soil treated as composite material. Principles of structure design”(in polish), IBW PAN Gdańsk, p.154, 2001
[10] http://www.sandomierz.pl/en/about-city/monuments/the-castle
[11] A. Sawicki, “Mechanics of Reinforced Soil”, A.A.Balkema, Rotterdam, 2000.