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Extent of geotechnical site investigations for buildings in Estonia

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Abstract. Numerous researchers have described problems encountered during the construction and performance of a building that result from inadequate site investigations (SI). The type and coverage of in-situ tests can significantly affect the quality of SI results. The aim of this study is to explore the amount and methods of SI in Estonia during the last eleven years. Site investigations data from 92 private and public buildings were collected and analyzed. Both quantitative and qualitative research methods were adopted to identify the most commonly used in-situ and laboratory methods according to different soil types and building height. The impact of the SI contractor was analysed as well. It was found that the costs of investigations constituted approximately 0.1% of the building tender cost for two- to six-storey buildings. Almost half of the SI contractors were designers too. Regardless of the contractor of SI and the soil type, the extent of SI was always similar. The majority of the investigations were conducted only in one stage. Dynamic probing was the most frequent in-situ testing method. The amount and quality of SI was found to be too low for a reliable and optimum design.

1. Introduction

Many recent studies have proven that a major element of technical and financial risk in civil engineering projects lies typically in the ground [1]. Foundation failures are often caused by inadequate geotechnical investigations [2]. The cost of foundation works comprises a considerable part of the total construction costs. However, an engineer must design a foundation solution that is safe and fulfills the service life requirements, such as allowed settlements. Besides, the load-bearing capacity of the foundation must be secured. At the same time, a good engineer should provide economical solutions to the clients. As a result, technical solutions of the buildings, including foundations, must be optimal. An engineer can only fulfil the assignment by means of proper qualification and accurate basic data. For a structural engineer, geotechnical conditions below the building have the same importance as the definition of accurate foundation loads. A minimum initial cost of investigations can lead to significant cost over-runs [3, 4].

Contractor awareness of the sufficient amount and quality of site investigations is critical to achieve a high-performing foundation structure [5]. The competence of the client may be inadequate to evaluate the quality and amount of site investigations, necessitating the involvement of an experienced geotechnical consultant [1]. A key aspect of optimal SI is to carry out the survey in many stages [6], involving appropriate investigation methods and hardware [1, 7, 8, 9]. In Estonia, it is common to conduct investigations in one stage.

The ratio range between the SI cost and the total building construction cost could be one solution to determine an optimal survey extent. Previous studies have reported that the optimal SI expenditure should be at least between 0.05% and 0.42% of the construction cost [10, 11, 12, 13]. This domain of research has been neglected in Estonia. The aim of the present study is to review the amount and methods of site investigations in Estonia. A questionnaire was sent to private and public institutions and digital data and blueprints were collected or copied, systematized and analyzed. Complete data from 92 building construction sites were received in total throughout Estonia from different geological conditions. This study points to the bottlenecks of the site investigations in Estonia and helps to compose the investigation plan for scientific SI using the modern soundings like SCPTu. The aim is to use these results to optimize the extent of SI for the buildings in Estonia.

2. Importance of geotechnical investigations

2.1. Optimal extent of geotechnical investigations

The ground is a highly uncertain and site-specific engineering material. Even though Eurocode 7 part 2 EN 1997-2:2007 [14] has guidelines for locations and depths of the geotechnical investigation points with the recommended minimum number of tests for one soil stratum, it is still unsolved how to convert the quality of a geotechnical investigation into a measurable context [15].

The Eurocode is based on the partial factor approach (PFA), including also the load resistance factor design (LRFD) method. According to Eurocode 7 part 1 EN 1997-1:2004 [16], the partial factor γ_M applied to soil-strength properties is fixed. The characteristic value for soil properties is defined as the cautious estimate of the value affecting the occurrence of the limit state, including all relevant, complementary information [16]. Statistical methods can be used, if there is enough test results. When statistical methods are applied the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5 % [17]. Although covariance describes the variability factors together, it does not depend on the design parameter itself. It also corporates circumstances, model transformation and the uncertainty of the measurements [18]. Hence, an important question is how to adjust the safety factor applied to the soil-strength properties in a limit state depending on the uncertainty related to the inherent variability and to the extent and quality of the geotechnical site investigation. The impact of random measurement error and statistical uncertainty on the design value of soil-strength properties can be decreased by increasing the site investigation expenditure. Moreover, by cross validating different geotechnical site-investigation methods attracting Bayesian analysis transformation uncertainty, which to a large extent is systematic, can be reduced [15]. Furthermore, reliability-based design (RBD) should be implemented into design guidelines at least in the most demanding cases in the future. Probabilistic treatment is an essential component of reliable and economic geotechnical design [18, 19].

Previous geotechnical investigations have identified the ratio between the site investigation cost and the building construction cost [3, 6, 10, 11, 12, 13, 20]. However, regulation determining the proportion of geotechnical investigations to the cost of the building. Despite many studies aiming to obtain the optimal ratio rate for geotechnical investigations have yielded different results. Rowe (1972) estimated the building cost of site investigation to range from 0.05% (light buildings) to 0.22% (heavy buildings). According to BRE Digest 322 [11], the minimum extent of geotechnical investigation from the building cost of low-rise buildings should be 0.2%. Goldsworthy et al. [12] clearly showed that in most cases, the optimal site investigation expenditure is approximately 0.2% to 0.3% of the construction cost. This result should be considered an absolute minimum site investigation effort. Based on a UK case study [13], it was proved that a minimal figure for an adequate site investigation would be 0.42% of the total construction cost of the project. For every building project, an optimal extent and cost of geotechnical investigation would provide a minimum cost for the construction.

An optimal extent of a geotechnical investigation for every particular building depends on the type of the construction and complexity of geotechnical terms. A higher final cost of the building will result from a smaller extent of the geotechnical survey than the optimal. At a greater extent of a geotechnical survey than optimal, the final cost of the construction will rise only little [12, 21, 22] text.

2.2. Factors which affect moderately the extent and quality of geotechnical investigation

Imperfect geotechnical investigations often begin from the client of the survey. Who would be the best client to order a geotechnical investigation? Should the survey be planned and ordered by a designer, an investigator or a client? A survey in Japan [5] showed that the best result could be achieved, when the client of the investigation was a designer. 61% of the respondents considered that, in an ideal situation, the designer should be responsible for planning the geotechnical investigation and only 25% considered it to be the responsibility of the investigator. According to the survey, the client plans and orders the investigation most frequently.

During planning and conducting of the geotechnical investigation, an experienced geotechnical consultant must be involved. As the expertise is not held within the project design group, geotechnical specialists should be added to the team [1].

A geotechnical consultant has to be the planner of the geotechnical investigations to control the execution and provide recommendations for the design of the foundation to avoid over-designed or under-designed foundation solutions. When choosing an investigator, the experience of the geotechnical consultant rather than the price must be the most important requirement [23].

To improve the quality of geotechnical investigations it is essential to perform the investigation in many stages. EC7-2 [14] states that site investigations should be accomplished in stages, depending on the questions that appear during planning, designing and building.

Jaksa [6] concluded that it is reasonable to divide SI into two stages: preliminary and that followed by a detailed investigation. Using soil parameters found in this way allow a geotechnical engineer to make accurate calculations that lead to an economical foundation solution.

Geotechnical investigations conducted in two stages determine geotechnical terms to be for placing buildings in situ and ideally, it also helps to decide the volume and structural solution of the building. Preliminary investigations help to develop more appropriate foundation solutions for the site and as a result, it is possible to compose accurate terms for a detailed investigation.

To avoid imperfect geotechnical investigations, it is not generally necessary to conduct more expensive surveys, but rather perform reasonably planned geotechnical investigations [1]. Making boreholes in dense net according to routine methodology is expensive. Instead, it is reasonable to focus on the areas requiring specific information.

Even though in-situ testing has evolved and improved over the past 25 years, several outdated and inadequate tests remain in common use in many parts of the world. Around the world, one of the oldest and most commonly adopted methods is still the standard penetration test (SPT) [9]. Mayne et al. [8] are right pointing to the false sense of reality in the geotechnical engineers`s ability to assess each soil parameter from a single N-value. Robertson et al. [9] recommend geotechnical engineers in the 21st century to steadily forsake this crude, unreliable in-situ test.

Failmezger [7] substantiated why shear strength correlations with SPT N-values tend to be conservative and crude. Quasi-static cone penetration tests CPT and the dynamic SPT tests strain the soil to failure. The results therefore provide strength parameters that represent failure. The stiffness increases significantly as overconsolidation increases (due to past stress history). As a result, modulus correlations with strength extrapolated from plastic (failure) behaviour to elastic behaviour necessarily include significant scatter. Modulus correlations with strength extrapolated from plastic (failure) behaviour to elastic behaviour necessarily include significant scatter. It typically leads to a conservatively chosen modulus. To reduce this conservatism, site-specific correlations with more accurate lab or in-situ tests must be made [7].

2.3. Outcomes of poor geotechnical investigation (The impact of limited geotechnical investigation)

In any geotechnical design, SI are essential, as inadequate characterization of the subsurface conditions may result in either costly over-designed or under design, which may lead to potential failures [24]. Inadequate geotechnical investigations force the geotechnical engineer to reduce risk of failure by over-designing the foundation, like Pohl [25] and Jaksa et al. [26] have reported. According to research in Canada, every third foundation failure is caused by inadequate site analyses [27]. In the USA, geotechnical input data were analyzed from 89 underground projects [3], with the conclusion that in 85% of the cases, claims and additional outgoings were the result of imperfect geotechnical investigations.

In the survey of the National Economic Development Office (NEDO), 56 industrial buildings were analyzed and it was concluded that approximately half of them overran their planned construction times by one month or more. 37% of the case studies suffered delays due to ground problems. The study performed by NEDO also showed that the amount of cases where poor geotechnical investigations led to a delay was significant [28]. Of 8,000 commercial buildings, a third overran by more than a month and a further third by up to a month [29]. Half of a representative group had suffered delays due to unforeseen ground conditions. Chapman [30] has demonstrated that while foundations are a relatively small part of the overall project cost (perhaps 7%), their problems can be responsible for half of significant project delays, occurring some 17–20% of the time.

According to the Building Research Establishment [11], too little attention has been paid to site investigations for low-rise buildings. Moreover, due to claims, the UK National House Building Council pays out 5-11 million pounds every year. More than half of the claims are the result of geotechnical problems [31]. Main geotechnical problems [1] related to low-rise buildings are:

Different settlements of heavy foundations or floor slabs
- Soft spots spread under footings on clay soils
- Growth or removal of vegetation on expansive clays
- Collapse settlements on pre-existing made ground
- Surface subsidence due to underground mining
- Self-settlement of poorly compacted fill
- Heavy floor slab on unsuitable fill material

Soil failure
- Failure of foundations on very soft subsoil
- Instability of temporary or permanent slopes

Chemical processes
- Groundwater attack on foundation concrete
- Reactions due to chemical waste or household refuse

Variations during construction
- Removal of soft spots to increase depth of footings
- Dewatering problems
- Piling problems

Based on the studies reported here, it can be concluded, that these problems affect building duration significantly.

3. Research material and methods

During this study, data about the completed buildings or those under building process were collected in 2015-2016 in Estonia. The following data were collected and entered into the database

- Height of the building
- Foundation project to figure out type of foundation and predominant soil type
- Site investigation report to get information about client, soil characteristics, testing methods and testing equipment
- Site investigation cost and time
- Building construction cost and time

Information was collected by emailing, phoning, taking photos and saving information to the memory stick. Different sources were involved:

- Site investigation companies 8 pcs
- Building and development companies 31 pcs

- Design companies 19 pcs
- National institutions and companies 20 pcs
- Ministries 11 pcs
- Local governments 56 pcs
- Private enterprises 12 pcs

Altogether, 157 different sources were used. The number of objects was 195, including 92 objects with complete data which were inserted into the database. The smallest building in the database is a residential house at 188 square meters and the largest is a supermarket at 123 818 square meters. Only two residential houses were entered in the database. Most of the buildings were hotels, schools, supermarkets and business centres, apartment buildings, storehouses, sports buildings, industrial and manufacturing buildings. All costs in the database include vat.

Most commonly, the reasons for not entering object information into the database were as follows: no site investigation available for the building; lack of the site investigation cost (mostly builidings older than ten years); based on one site investigation more than one building erected at different times; site investigation made in consideration of permanent buildings as well. Building construction and site investigation costs were very sensitive information to obtain. Some of the agreements were confidential and it was impossible to receive information about the prices.

In the database, information was divided into different groups. Height of the buidlings was divided into three groups: one- to two-storey, two- to six-storey and higher buildings. Only low-rise buildings were included into the first group. The second group contained buildings that had different parts with different storeys (e.g., one part had two storeys and another part had three storeys). Decisive soil was divided into five groups: fill; clay soils which determine settlements of foundations ($E<5$MPa); clay soils which determine the load bearing capacity of foundations; sandy soils and sandstone; limestone.

Types of foundations were divided into four groups: piles, wedge piles, plate foundations and shallow foundations except for plate foundations. Actors of site investigations were divided into three groups: designer, building company and client. From SI reports, the methodology of the investigations was studied to find the proportion of in situ and laboratory methods. The t-Test was used and the mean values of two groups were compared.

4. Results and discussion

Main results are presented on the bar charts in figure 1 to figure 6. To explain client's proportion of site investigations, the chart in figure 7 was constructed. In the first four graphs, the extent of investigations is presented on the x-axes. Only between building groups one- to two-storey and two- to six-storey, a statistically significant difference was found ($p=0.00015<0.05$). In this study, no significant difference appeared between all other groups.

The extent of investigations according to the height of the builidng (figure 1) shows clearly that site investigations for two- to six-storey buildings are drastically smaller than for low-rise or higher buildings. Mean value for proportional cost for two- to six-storey buildings is 0.054%. For 1 to 2 storey buildings, mean value of the proportional cost of SI is 0.17% and the mean value for the higher building group is 0.12%. Rowe [10] suggested SI costs percente of capital cost of works for light buildings as 0.05%. This number seems to be too little. According to Digest 322 [11] it should be for low-rise buildings at least 0.2%.and Hytiris et. al [13] proved that minimum percente should be 0.42%. This paper demonstrates that the percente is close to 0.2%, however, it is approximately two and a half times smaller than Hytiris et. al counseled. Goldsworthy et. al [12] recommended 0.2% to 0.3% as a approximate investigation expenditure of the construction cost for 5-storey structure. This research shows clearly in Estonia for 2 to 6 storey buildings the percent is drastically low and should be at any rate 4 to 6 times bigger. For heavy buildings according to Rowe [10] the minumum percente of SI should be 0.22%. This number is almost two times bigger than for the higher building group in this paper.

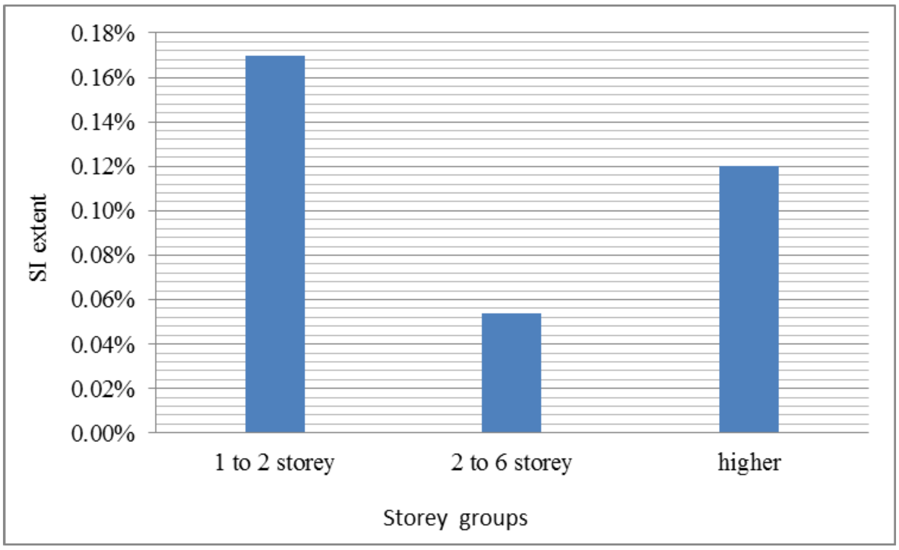

Figure 1. Dependence of the proportional cost of SI on the height of the building

Decisive soil has very little effect on the extent of investigations (figure 2) and mean values are between 0.073% (limestone) and 0.12% (sandy soils and sandstone). It is remarkable that one of the smallest extents of site investigation (0.078%) is in clay soils, which determine settlements of foundations (E<5MPa).

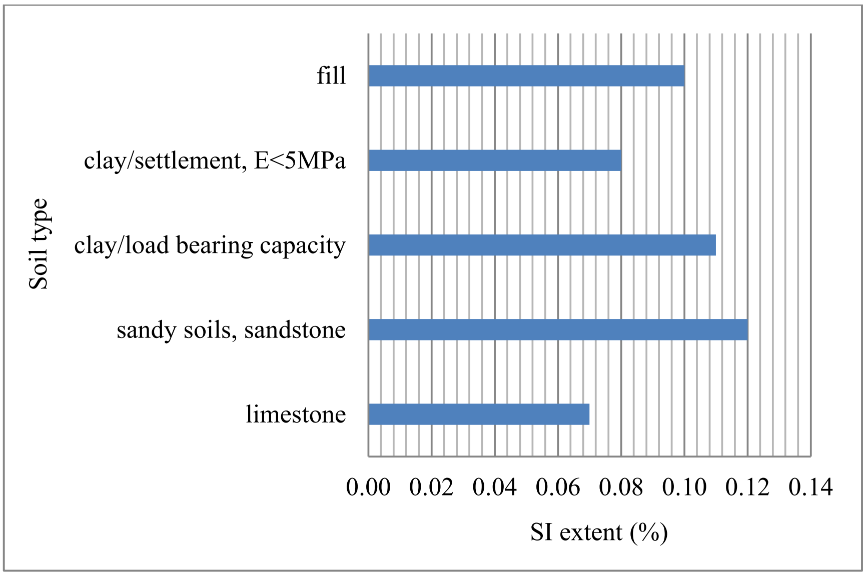

Figure 2. Dependence of the proportional cost of SI on soil

Type of a foundation also has very little effect on the extent of investigations (figure 3) and mean values are between 0.072% (plate foundation) and 0.114% (shallow foundation). The proportional cost of SI for shallow and pile foundations is nearly the same.

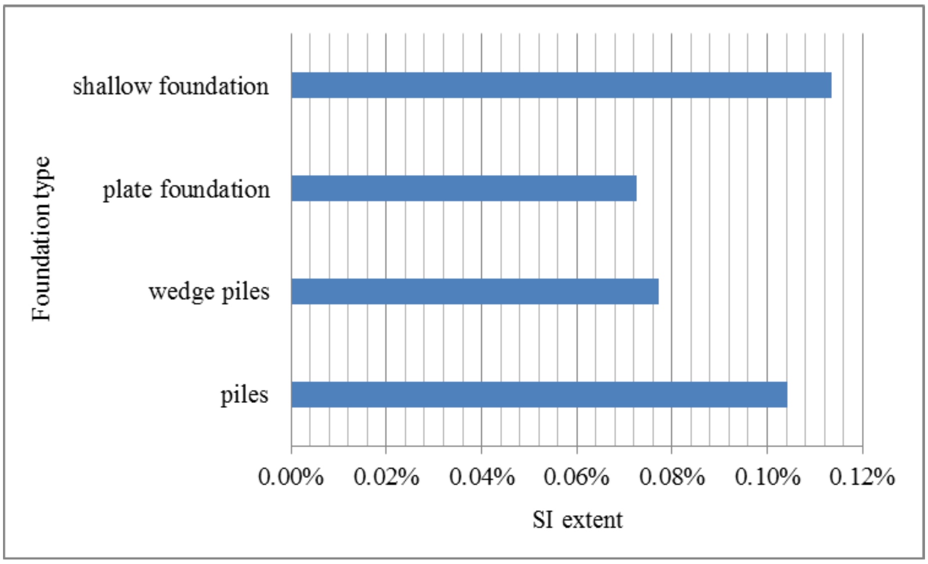

Figure 3. Dependence of the proportional cost of SI on the foundation type

Client has no effect on the extent of investigations (figure 4), percent varies only a little. Mean proportional values are between 0.103% (designer) and 0.119% (building company). Client`s group represent contractors who often has no experience according to site investigations. Building company`s and designer`s group represent contractors who frequently subscribe to SI and should have experience. Proficient contractor is expected to order sufficient investigations not only making decision based on the price of the work. However, even costs of SI point to the situation in Estonia where the investigator frequently compiles the investigation plan goaling the lowest price to get the job.

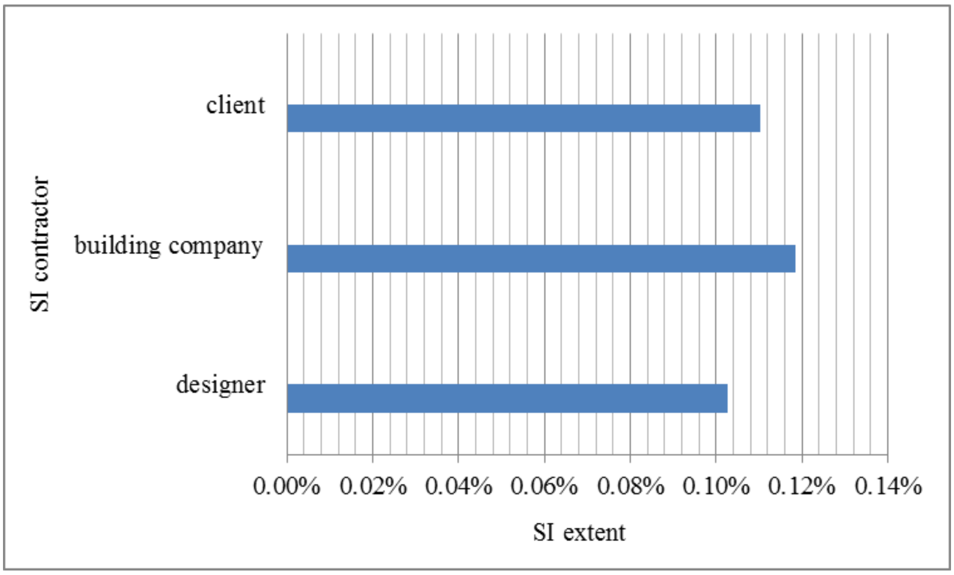

Figure 4. Dependence of the proportional cost of SI on the client of the SI

The next two charts present the cost in euros on the x-axis and building cost (figure 5) compared to the investigation cost (figure 6). Mean building cost for one- to two-storey buildings (35 objects) is 3 522 876 euros and at the same time, the mean site investigation cost is 2812 euros. The mean building cost of two- to six-storey buildings (49 objects) is 8 219 190 euros and the mean site investigation cost is 2371 euros. Higher buildings (8 objects) have the highest mean building cost of 13 305 000 euros and the highest mean site investigation cost of 8467 euros. It is remarkable that two- to six-storey building group has the lowest value of the mean cost of investigation.

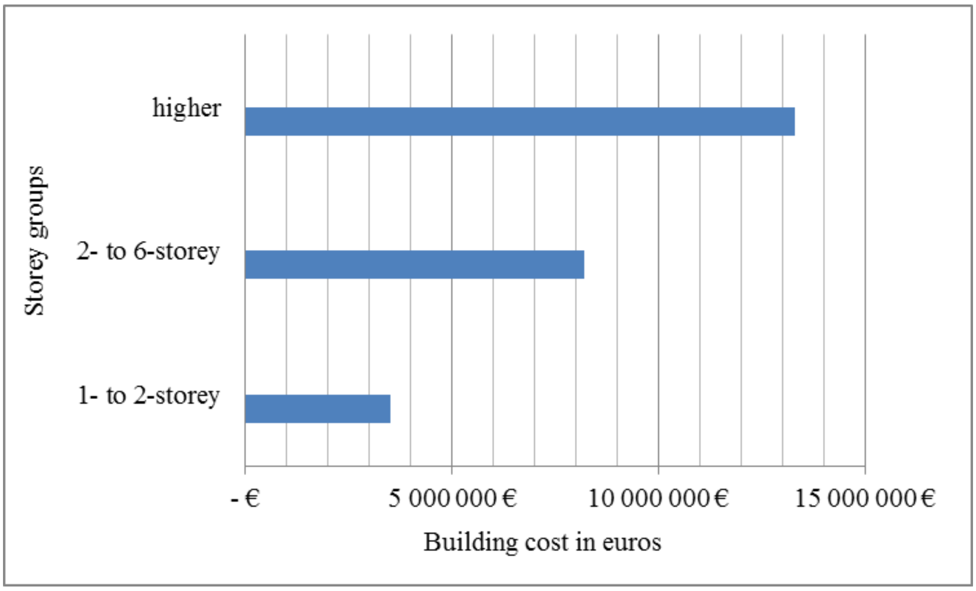

Figure 5. Mean cost of the three groups of buildings

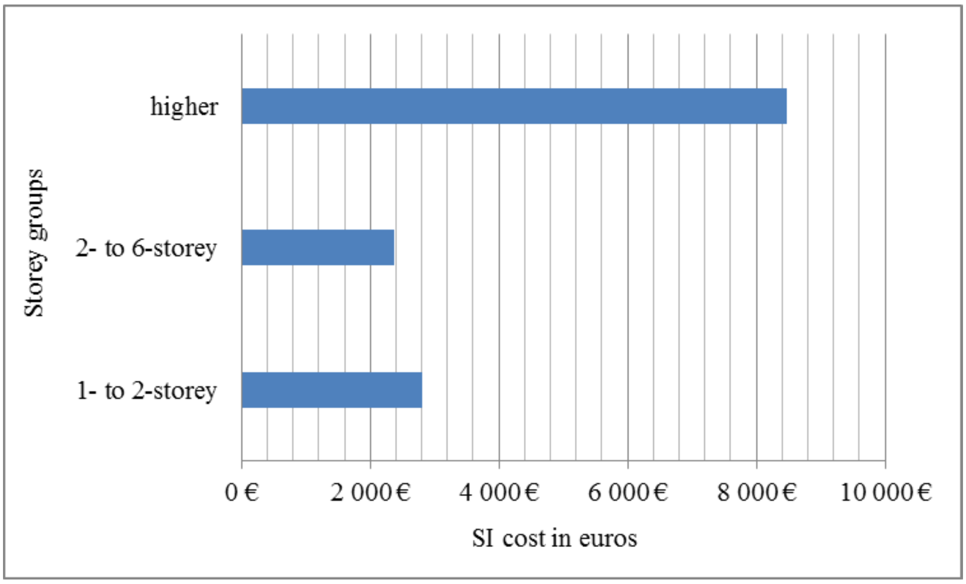

Figure 6. Dependence of the mean cost of the SI on the height of the building

Table 1 shows all soil testing methods from the database of site investigations. Different boring methods were used to appoint types of soil whereas only disturbed soil was collected. Commonly, type of soil was determined visually. Atterberg limits were defined in eight cases and sieve analyses were made in twelve cases in laboratory. The most popular penetrating method in Estonia is the Dynamic Probing Super Heavy test. Probe of the Dynamic Probing is presented in figure 7. To evaluate soil strength and compressibility, the hard dynamic penetration test (DPSH) was made nearly three times more often than the Static Cone Penetration test (CPT). The most frequent laboratory test was the moisture content evaluation. Soil compressibility or strength was determined only a few times in laboratory.

Table 1. Soil testing methods in Estonia

In situ testing / number of cases	
Boring (auger drilling)	74
Dynamic Probing Super Heavy (DPSH) - no sampling	48
Cone Penetration Test (CPT)	15
Dynamic Probing Light (DPL)	5
Vibro penetration (one company in Estonia used it in the nineties-they measured the speed of vibration of rod in soil)	5
Vane shear test (VST)	1
Laboratory testing	
Moisture content	20
Sieve analysis	12
Atterberg limits	8
Pollution/corrosion	7
Direct shear test	3
Unconfined compression test	2
Triaxial test	1
Hydrometer analysis	1
Organic content of soils	1
One-dimensional compression	1
Consolidation test	1

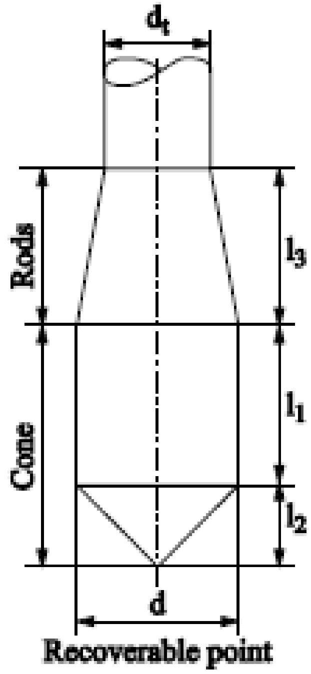

Figure 7. Fixed cone dynamic penetrometer [32]

In our study, slightly over half (52%) of the contractors of the investigation were designers and approximately one third (32%) were clients (figure 8). The smallest contractor group was the building companies (16%).

In Estonia it is very common to over-design foundation solutions. Generally, minimum amount of geotechnical site investigations are made in one stage. To avoid failure, higher safety factors have been applied for approximately defined soil parameters, which leads to over-designed foundations. A big problem in Estonia is that the amount of geotechnical engineers or other persons, who understand the meaning of SI, is small. Often the structural engineers design the foundations, but they lack the geotechnical experience and knowledge. There are very few engineers who are able to place doubt on the amount and quality of SI and hence, on foundation solutions. Often, it is in the client's interest to start construction quickly. The clients and contractors are seldom willing to give additional time for a close geotechnical survey and foundation redesign, which would probably lead to an optimal solution. Generally, an optimized foundation solution is smaller, economical, more environmental-friendly and it takes less time to erect than bigger one.

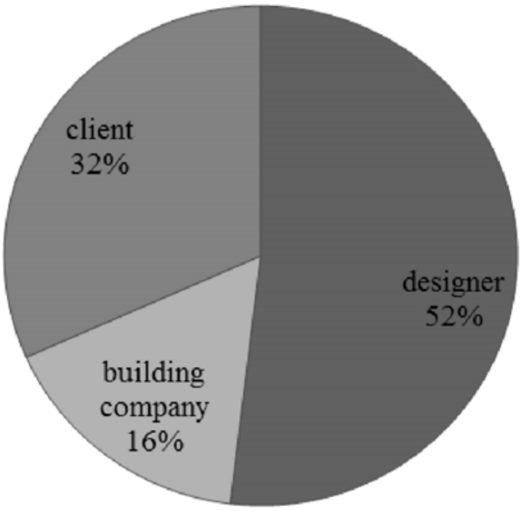

Figure 8. Contractor of the SI

5. Conclusion

During the study, foundation and SI data about the completed buildings or those under building process were collected in 2015-2016 in Estonia. According to previous research, accurate planning and completion of geotechnical investigations enable saving money from surveys and the construction cost. Thus, during planning and geotechnical investigations, it is essential to involve experienced geotechnical consultants and carry out surveys in two stages: preliminary and that followed by a detailed investigation. Effective geotechnical investigations help to reduce under-designed and over-designed foundation solutions, failures and claims. It is important to increase the awareness of clients accordingly.

In Estonia, no studies focused on the optimal extent of geotechnical investigations have been conducted although the need is obvious. Each building project can be supplied an optimal extent and cost of a geotechnical investigation that provides a minimum cost for the construction. According to BRE Digest 322 [11], the minimum extent of geotechnical investigation from the building cost of low-rise buildings should be 0.2%. It is necessary to study the problem related to high-rise buildings, bridges and port facilities as well.

Our findings show that in Estonia differences in soil conditions, types of foundations or client types have no effect on SI. Extent of investigations was quite similar, constituting approximately 0.1% of the building cost. It is most remarkable that the extent of site investigations for two- to six-storey buildings was more than three times lower than that for one- to two-storey buildings. Further studies are required here. Most commonly, investigators use boring to visually assess the type of soil and hard dynamic penetration equipment to present friction angle, cohesion and module of deformation. The laboratory tests are made rarely to determine soil strength or compressibility properties. It gives evidence of the approach that frequently an investigator decides the site investigation extent and methods. For a client, the lowest investigation cost is the decisive criterion to make the contract.

In the next study, it is required to analyze project solutions (already built or upcoming) where doubts are placed on poor extent or quality of SI. As a result, an alternative foundation solution could be constructed including comparisons of the cost.

Acknowledgements

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References

[1] Institution of Civil Engineers 1991 *Inadequate site investigation* (London: Thomas Telford) p 26

[2] Nordlund R L and Deere D U 1970 Collapse of Fargo grain elevator *J. Soil Mechanics and Foundations Division*, ASCE **96**(2) pp 585-607

[3] National Research Council (NRC) 1984 Geotechnical site investigations for underground projects *US National Committee on Tunneling Technology* **1** (Washington: National Academy Press)

[4] Littlejohn G S, Cole K W and Mellors T W 1994 Without site investigation ground is a hazard *Proc. Inst. Civ. Engrs Civ. Engng* **102**(2) pp 72-8

Whyte L L 1995 The financial benefit from site investigation strategy *Ground Engng* **28** pp 33-6

[5] Shirato M, Fukui J and Matsui K 2002 Present situation regarding ground investigations and the determination of geotechnical parameters in Japan *Foundation Design Codes and Soil Investigation in view of International Harmonization and Performance Based Design*, ed Honjo Y, Kusakabe O *et al* (Lisse: Swets & Zeitlinger) pp 237-243

[6] Jaksa M B 2000 Geotechnical risk and inadequate site investigations: A Case Study *Australian Geomechanies* **35**(2) pp 39-46

[7] Failmezger R A and Bullock P J 2008 Which in-situ test should I use?—A designer's guide *Proc. of Ohio River Valley Soils Seminar 39* ASCE Cincinnati

[8] Mayne P W, Coop M R, Springman S M, Huang A B and Zornberg J G 2009 Geomaterial behavior and testing *State of the Art Report #1 Proc. of the 17th ICSMGE* Alexandria pp 2777-872

[9] Robertson P K 2013 The James K. Mitchell Lecture: Interpretation of in-situ tests—some insights *Geotechnical and Geophysical Site Characterization 4* ed Coutinho R Q and Mayne P W (London: Taylor & Francis Group) pp 3-24

[10] Rowe P W 1972 The relevance of soil fabric to site investigation practice. 12th Rankine Lecture *Géotechnique* **22**(2) pp 195–300

[11] Digest 322 1987 Site investigation for low-rise building: procurement *Building Research Establishment* (Bracknell: HIS BRE Press)

[12] Goldsworthy J S, Jaksa M B, Fenton G A, Griffiths D V, Kaggwa W S and Poulus H G 2007 Measuring the risk of geotechnical site investigation *Probalistic Application in Geotechnical*

Engineering, Geotechnical Special Publication No 170 Proceedings of the Geo-Denver Symposium, ed Phoone K K *et al* ASCE

[13] Hytiris N, Stott R and McInnes K 2014 The importance of site investigation in the construction industry: a lesson to be taught to every graduate civil and structural engineer *World Transaction on Engineering and Technology Education* **12**(3) pp 414-19

[14] 2007 EN 1997-2:2007 *Eurocode 7: Geotechnical design – Part 2: Ground investigation and testing* (Brussels: European Committee for Standardisation)

[15] Prästings A, Larsson S and Müller R 2017 Optimizing geotechnical site-investigations *Proc. of the 19th ICSMGE* Seoul pp 639-42

[16] 2004 EN 1997-1:2004 *Eurocode 7: Geotechnical design – Part 1: General rules* (Brussels: European Committee for Standardisation)

[17] Frank R, Bauduin C, Driscoll R, Kavvadas M, Krebs Ovesen N, Orr T and Schuppener B 2004 *Designer's Guide to EN 1997-1 Eurocode 7: Geotechnical design – General rules* (London: Thomas Telford) p 216

[18] Fenton G A and Griffiths D V 2008 *Risk assessment in geotechnical engineering* (New York: John Wiley & Sons) p 480

[19] Phoon K K 2015 Reliability of geotechnical structures *Japanese Geotechnical Society Special Publication* **2**(1) The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering pp 1-9

Ching J Y, Hu Y G and Phoon K K 2016 On characterizing spatially variable soil shear strength using spatial average *Probabilistic Engineering Mechanics* **45** pp 31-43

Ching J Y, Wu S S and Phoon K K 2015 Statistical characterization of random field parameters using frequentist and Bayesian approaches *Canada Geotechnical Journal* **53**(2) pp 285-98

[20] Clayton C R I, Simons N E and Matthews M C 1982 *Site Investigation* (Londin: Granada Publishing) p 424

Peacock W S and Whyte I L 1988 Site investigation practice *Mun. Eng.* **5** pp 235-45

[21] Jaaniso V 2002 Geotehnilised uuringud Eestis – probleemid ja perspektiivid *XII Eesti Geotehnika Konverents* (Tallinn: Eesti Geotehnika Ühing) pp 10-2

[22] Jaksa M B, Goldsworthy J S, Fenton G A, Kaggwa W S, Griffiths D V, Kuo Y L and Poulus H G 2005 Towards reliable and effective site investigations *Géotechnique* **55(2)** pp 109-21

[23] Moh Z C 2004 Site investigation and geotechnical failures *Proceeding of International Conference on Structural and Foundation Failures* Aug 2-4 2004, Singapore

[24] Goldsworthy J S, Jaksa M B, Kaggwa W S, Fenton G A, Griffiths D V and Poulos H G 2004 Cost of foundation failures due to limited site investigations *Proceeding of International Conference on Structural and Foundation Failures* 2-4 Aug Singapore pp 398-409

[25] Pohl C 2011 Determination of characetistic soil values by statistical methods *Proc of. ISGSR 2011* Munich

[26] Jaksa M B, Kaggwa W S, Fenton G A and Poulos H G 2003 A framework for quantifying the reliability of geotechnical investigations *Proc. 9th Conf. Appl. Stat. Probabil. Civ Engng*, San Francisco 2 pp 1285-91

[27] Marshall R P 1999 Foundation failures in the new residential construction. *Durability of Building Materials and Components 8* ed Lacasse M A and Vanier D J (Ottawa: Institute for Research in Construction) pp 1011-21

[28] National Economic Development Office (NEDO) 1983 Faster building for industry. London

[29] National Economic Development Office (NEDO) 1988 Faster building for industry. London

[30] Chapman T J P 2008 The relevance of developer cost in geotechnical risk management *Foundations: Proc. of the 2nd BGA International Conf. on Foundations* ICOF2008 ed Brown M J, Bransby M F *et al*, (Watford: IHS BRE Press) pp 3-25

[31] Johnson R 1990 Symposium report on quality management in geotechnical engineering *Ground Engng* **23** p 23

[32] Monnet J 2015 In situ tests in geotechnical engineering (New York: John Wiley & Sons), p 39