A Review of the Advancement of Helical Foundations from 1990-2020 and the Barriers to their Expansion in Developing Countries

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Abstract

The use of piles, helical anchors, in general, helical foundations has considerably increased in the last 30 years. The adoption of this technology in the international and domestic codes of each country, as well as in research and studies, and, finally, the publication of numerous books and papers in this area, and the existence of manufacturers' products, committees, and contractors of this technology has contributed to its expansion and development. However, such methods have progressed at a very slow pace in many countries, especially in developing countries. This paper attempts to assess the global advancement of the helical foundations by reviewing 292 papers from 1990 to 2020 and comparing the related research findings. This will help clarify the issue and determine the scope of technological progress. On the other hand, collecting valuable papers in this area will make it easier for researchers to make further research. Subsequently, the characteristics of this technology are highlighted and the reasons for its lack of progress in developing countries are addressed. For this purpose, a questionnaire is sent to researchers, developers, designers, and contractors of the geotechnical projects. The purpose of this questionnaire is to specify the type of existing projects, the soil type of project site, the degree of familiarity with the helical foundation technology, the reasons for not using this method, and the solutions available to expand and develop this method. Finally, there are suggestions to develop this approach and the issues that need further research.

Keywords: helical pile, anchor, micropile, clay, sand, soil nail.

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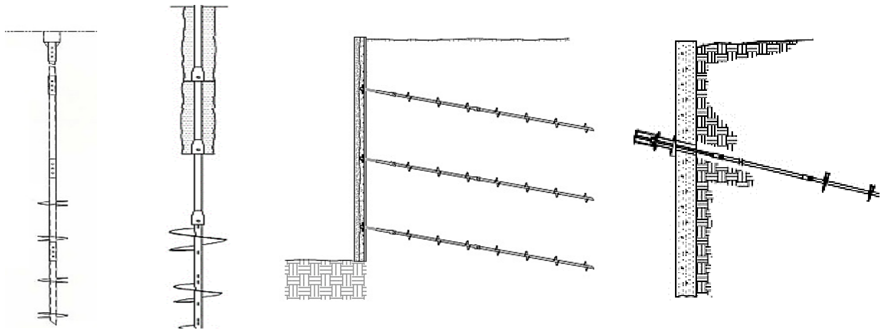
Introduction

The helical members include a steel shaft with one or more helices attached to it. In multi-helix anchor, the pitch and center-to-center spacing of the helices are in a form that the upper helix follows the lower helix path. Thus, the amount of soil disturbance is reduced. The helical foundations are known by many names, such as screw pile, screw anchor, helical anchor, helical pile, helical pier, helix pier, torque pile, torque anchor, helical micropile, helical soil nail, etc... . Although these terms are used in almost the same system, they have differences. The difference in these systems is due to the design, application, and changes in the configuration of the helical foundations.

The term "helical pier" often refers to shallow foundations, while the "helical pile" refers to deep foundation systems (Fig. 1a). "Helical anchor" is a term used for a narrow helical pile (with a thin shaft), which main or predominant loading is tensile. The helical micropile, commercially used since 2000, is a helical pile with grouted shaft (Fig. 1b). The helical soil nail is also a helical anchor that is used to stabilize the walls and slopes (Fig. 1c). The helical soil nail was first used commercially in 1996 for the construction of a wall with a height of 6.7 m [1]. Helical anchor and helical soil nail both consist of a shaft and several helices. The Helical anchor has fewer helices than the helical soil nail and is usually limited to three plates (Fig. 1d). In the helical anchors, the diameter of plates can be different from each other while in the helical soil nails the diameter of plates is equal. In the helical anchoring method, the bearing plates are far from the slip surface, while in the helical soil nailing method, the entire soil mass is reinforced. Finely, helical anchors are usually post-tensioned after installation, while the helical soil nail activation requires the displacement of the wall [1-3].

Helical foundations have many advantages. The easy installation in the collapsible soils, the lack of spoils, and the lack of need for drilling are some of the most important advantages of this method. Monitoring the installation torque will ensure the correctness of the design assumptions and correct implementation of the procedure. In this method, post-tensioning and testing immediately after installation are possible. The implementation cost of these foundations is reasonable because of the high speed of operation, grout exclusion, cheap and affordable equipment, and the possibility of operating in areas with limited access. These members are compatible with the environment and can be used for a wide range of soils and weather conditions. Also, it is possible to install them under the water table. If the helical members are installed in the wrong location, they can be easily displaced and reinstalled. Also, as in the case of temporary bracing, the helical anchors can be displaced and altered if desired [2-7].



(a) (b) (c) (d)

Fig. 1. Configuration differences of helical members (a) Helical pile (b) Helical micropile (c) Helical soil nail (d) Helical anchor

A disadvantage of this method is to prevent the proper replacement of these foundations due to the impact of rock or other obstacles on the installation route. In the past, the lack of corrosion protection and the limited capacity of these members were also the disadvantages of this method. With the advancement of science and the emergence of various methods of anti-corrosion, as well as the introduction of the helical micropile method and the increase in the power of executive equipment, these issues were resolved [8, 9].

Due to numerous advantages, these types of foundations have found many applications in a variety of projects. Today, helical anchors and piles are used in new projects for applications such as underpinning, wall stabilization, increasing new foundation capacity, solar panels maintenance, marine structures stabilization, wind generators, highway bridges, lighting, pedestrian bridges, signage, towers, pipeline anchors, and storage tanks. These helical members are also involved in repairing and improving existing foundations in applications such as seismic retrofitting, tie back and lateral stabilization, temporary maintenance, anchors for utilities, and conservation of historical and cultural heritage [2, 6, 7].

Considering the various applications of helical foundations, we have tried to provide appropriate information on this topic in three different sections. In many cases, in research projects and papers, new names are used for helical anchors or piles, or common names are used incorrectly and interchangeably, or there is a mismatch between the name chosen in the research project and the industrial name the investigated helical foundation.

In the first phase of this research, the related papers presented between 1990 and 2020 have been collected and classified. After classifying the literature works, to better review the literature, common questions were asked about the collected papers and answered. Finally, issues such as the impact of lateral loading and the anchor-pile groups are investigated.

In the second part of the paper, the questionnaire has been evaluated. The purpose of presenting the results of this questionnaire is to examine the reasons for the lack of progress in the technology of helical anchor and pile in developing countries. The type of projects carried out, the types of soils used, the reasons for the lack of progress, and suggestions for extending this method are widely discussed in the questionnaire and, finally, suggestions are made to improve this approach. In the third part of the paper, regarding the review of the papers and the results of the questionnaires, suggestions for further research in this field are presented. The overall goal of all studies is to develop this effective method throughout the world and its implementation in developing countries.

The advancement of helical foundations

To examine the advancement of helical anchor and pile technology, all available papers have been evaluated from 1990 to 2020, and questions have been asked about them and answered. A total of 292 papers have been collected and reviewed. This will help the other researchers in this area in their future research works. In the collected papers, attempts have been made to remove duplicates and to evaluate the research works published and presented valid journals and conferences.

1. The progress rate of helical foundations

The first question that comes to mind about this technology, is about the amount of work each year. Another issue is whether the helical anchors and piles are in progress, or with the advancement of other methods, they are replaced with other technologies. To answer this question, the publication year of the paper and the holding year of the conference has been evaluated and the number of works performed each year is specified (Fig. 2). The reason for choosing 1991 as the origin of the research time was four issues: 1) in previous years, some works have also been done in this area, but their collection is not feasible and they are not available in electronic resources. 2) Dispersion and discrepancy of the data; that is, the member called and discussed as the helical pile didn't have the shape and function of the current helical piles. For example, the belled pile which has a different mechanism is also evaluated under the theme of the helical pile. 3) The publication of a book named "Earth anchors" by Das (1990), which deals with the proper classification of anchors [10]. 4) The initiation of research by Ghaly et al. and Rao et al. about 1991 [11-17]. This research has been instrumental in the development of helical foundations and has been the cornerstone of many of the current research works. So we started our research review in 1991.

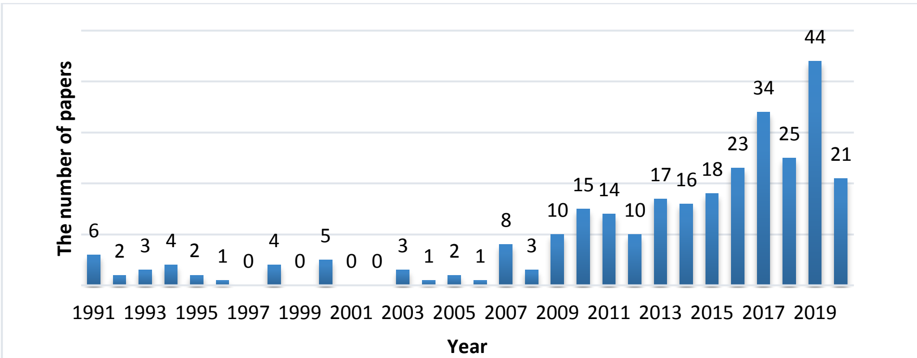


Fig. 2. The number of papers presented about the helical foundations from 1991 to 2020 [1, 7-9, 11-298]

From 1991 to 1993, perhaps are years of determination of the initial behavior of the helical piles and anchors in the clay and sandy soils under installation torque and application of the pullout and compression axial load. In these years, all experiments were performed by Ghaly et al. and Rao et al. [11-17, 24, 25, 128]. Finally, in 1993, Seider applied this technology in the field supported by an underpinning system [123]. From 1994 to 1996, can be considered as the years of expanding and completing initial research. In general, the most important research work done in these years is to study the performance of helical anchors and piles under the lateral and cyclic loading by Ghaly et al. and Rao et al. In these studies, the group behavior of the helical anchors has also been considered [26, 27, 119, 125, 136, 170, 229]. Unlike current helical anchors, in anchors provided by Ghaly et al, there is no distance between the helices. On the other hand, in the anchor provided by Rao et al, the distance between the helices is about 1.5D, which is less than the amount used in recent research.

From 1997 to 1999 can be considered years of evaluation and speculation of this technology. Because during these years, the initial studies were completed but research works didn't have a growing trend. Performing the test by Ghaly et al. on inclined anchors to increase the application of helical members may have been the most important research done in this period [23]. From 2000 to 2002, attempts have been made to create and develop another type of helical members (helical micropile), changing the configuration of helical members [8]. On the other hand, more researchers have been interested in this issue and tried to examine the various aspects of this technology. However, research works have been very limited during this period. The study of economic issues surrounding this technology [193] and the use of helical foundations in heavily loaded structures [9] are the most important research works carried out in this period. The period of 2003-2005 is the beginning of the numerical modeling of helical members. The modeling done in this period reduced the research costs. So, the first steps in the research development and expansion were taken in this period. The use of finite element analysis for the helical piles modeling has been used for the first time in this period [129, 168]. Increasing research works on grout usage in helical foundations technology can also be attributed to this period.

The period of 2006-2008 can be called the early years of the approval of helical foundations technology. In 2007, the Acceptance Criteria (AC358) for Helical Pile Systems and Devices was approved by the International Code Council Evaluation Service (ICC-SS) [299]. This approval was a big step in expanding this approach. The first three-dimensional modeling of the helical members and the initiation of research conducted by Tsuha et al, as well as Naggar et al, is related to this period [98, 100, 121, 130]. In 2009, the International Building Code also provided a standard procedure for the design, implementation, and testing of helical foundations [300]. Acceptance of this method in the internal codes of the countries, such as the Canada and Japan codes, also relates to this time limit [22, 301]. Providing early versions of various codes and guidelines, and computational and executive guidebook by manufacturing companies such as A.B.CHANCE, as well as the publication of a book named "Helical Piles" in 2009 by Perko, has contributed to the upward trend of research in this area around the world and has led to the expansion of research carried out in this field since 2009 to 2011 [3, 4]. Many researchers have begun their work during the same period and helped its expansion and development.

In this period (2009-2011), Sakr et al. researched the lateral loads applied on the helical foundations as well as on the function of the helical members in the oil sand [84, 137, 155]. Also, Lutenegger [117] and Merrifield et al. began their research as the first persons to study experiments on the helical anchor centrifuge model [21, 36, 167] in this period. Also, Tsuha et al. continued their research on the connection between the installation torque and the bearing capacity of the helical piles in these three years [83]. Sakr et al. were among the people who took effective steps in expanding and developing field research on the helical members. Study on high-diameter helical piles with a high bearing capacity [79, 153], field study on the walls stabilized by the helical soil nail method [1], and study on dynamic loads applied to helical anchors implemented in saturated and dry soils [34, 99], is only a small part of the research works and developments in this golden age. Also, the studies on the effect of grout on increasing the helical members' capacity and the impact of monotonic and cyclic loading types [58, 88, 102] were expanded in this period.

From 2012 to 2014, there has been a revision period in design methods regarding the latest codes and analytical models. Also, more sophisticated experiments using the most up-to-date methods have been done in this period. Moreover, the number of field studies on the effect of changing materials or the configuration of helical members on increasing the bearing capacity and investigating the effect of these members on soil types have increased during this period. A large part of the research carried out in this period is related to field studies conducted around the world [35, 40, 41, 44, 48, 56, 57, 59, 61, 74, 77, 80, 85, 86, 89, 96, 104-106, 118, 141, 144, 146, 147, 177]. Also, for analyzing helical members under dynamic and static loading, new methods such as centrifuge modeling and photo-elastic analysis have been used alternatively [42, 44, 48, 60, 114]. The serviceability and reliability of the helical foundations are also evaluated for the first time in this period [50, 65].

Between 2015 and 2020, the number of research works has increased, and much research has been conducted on all continents over these five years. Issues such as the behavior of the helical anchor and pile group [51, 225], the use of HeliCAP specialized software for the design of helical members [68], the use of helical piles in offshore structures [69, 70, 72, 75, 222], and research on the lateral bearing of helical anchors and piles [62, 116, 148, 149, 157, 179, 187-189, 201, 206, 217, 221] are cases where special research has been carried out on them. Also, physical modeling of helical piles using FCV [63, 95, 110, 186], studying on GFRP screws anchors [158], helical soil nails [163, 164, 169, 190, 200, 284, 294], using CPT test results to estimate the installation torque and bearing capacity of the helical piles [92, 143, 175, 226] are other issues that have been investigated. Some research has also been carried out on the changes in configuration, materials, and grout usage to increase the bearing capacity of the helical anchors and piles [293]. The reason for the decline in research works done in 2020 could be due to the lack of loading of papers from 2019 until the beginning of 2020. Undoubtedly, in 2021, the other research works carried out in 2020 can also be studied. Concerning Fig. 2, it is clear that research on helical foundations is expanding and many issues require further research.

2. Countries of expertise in the helical foundation field

Perhaps the study of countries that have done a lot of research in this area may help to continue research and understand the reasons for the lack of progress of this method in developing countries (Fig. 3). The name of the country is taken from the profile of the first author of each paper (his/her work or study place). It refers to a country where research has been conducted. The helical pile foundations were used in the early 19th century in England, but as it is known, most research has been done in countries such as Canada and the United States. This is due to the extent of their countries as well as the advancement and expansion of technology and industry in these countries. The largest and most advanced helical foundation companies are operating in Canada and the United States. Another point is the participation of 29 countries from five continents in this study, which reflects the spread of this method throughout the world.

This research team researched a helical anchor group used to stabilize walls and slopes [244, 298, 302-304], the pullout of helical anchor, and the use of grout injection to increase the bearing capacity of the helical anchors [293]. Also, a book is written in the Persian language for the development of various mechanical anchors [304]. In Fig. 4, the anchors and test boxes used by the authors are presented.

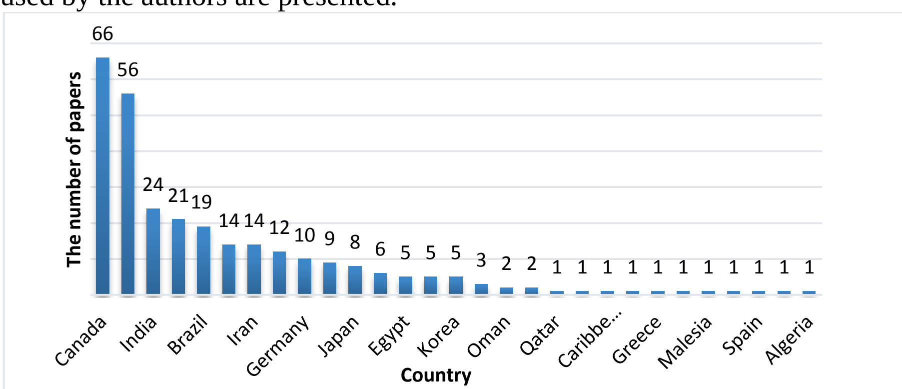


Fig. 3. The number of papers presented by each country about the helical members from 1991 to 2020 [1, 7-9, 11-298]

(a) (b)

Fig. 4. (a) 4 Type of anchors used (b) Test box

3. The type of helical member used

The next question is related to the type of member used. The research in developing countries can begin by asking which helical members are more useful. First, using the google trend, the number of searches associated with the keywords used in the field of helical foundations are identified throughout the world. The output of the results is presented in Fig. 5. The reason for starting a search since 2004 is launching this search engine this year. On the other hand, 4 words have been searched: "helical anchor", "screw pile.", "helical pile" and "helical pier". The words "helical micropile" and "helical soil nail" have not been searched because they are new and their application is very limited. Also, the search for "screw anchor" will not help the research because of the presence of a member with this name in other industries. As shown in Fig. 5, the word "helical pier" was initially searched more than other words. In recent years, the search for "screw pile" and "helical pile" has been more than "helical anchor" and "helical pier". As a result, it seems that the use of helical piles is more common than helical anchors.

For a thorough examination, the number of papers worked on each type of helical member has been investigated (Fig. 6). In the anchor group, the number of works related to helical anchors, helical soil nails, and narrow helical members under tensile force is presented. The reason for this classification is to prevent the dispersion of the topics. Because in some research works, the word "screw nail" has been used, but it is discussed about the helical anchor, or other nouns are used such as "screw anchor" instead of the helical anchor. It is not possible to differentiate and distinguish these research works from each other. On the other hand, any research in which the word "grout" is used alongside the "helical anchor or pile" is categorized in the subgroup of the helical micropile. Some researchers have used other names such as helical piles with grouted shafts. To prevent the dispersion of the topics, all of these cases are categorized into one group. The helical pier and the thick helical members under compressive force are also placed in the helical pile group due to having the same conditions as the helical piles.

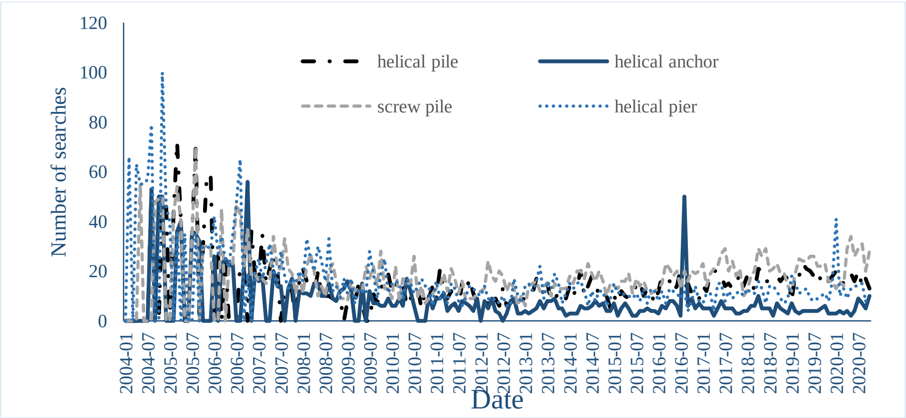


Fig. 5. Number of searches done about the helical foundations from 2004 to 2020 throughout the world

As it is obvious, the total number of completed papers in the various fields is more than the 292 papers reviewed; this is because some papers are related to several fields. For example, the research works conducted by Ponomarenko and Baranov, or Seider, have been related to both fields of the helical anchor and helical pile [43, 68]. In sum, most of the work has been done in the field of helical piles. It should be stated that helical piles are more useful than helical anchors and micropiles and more extensive research has been done on them. Of course, considering the volume of research works done, it is clear that the helical anchors also have a good performance. Due to the novelty of the micropile method in comparison with the helical anchor and pile methods, the number of research papers in this field is less than the latter ones.

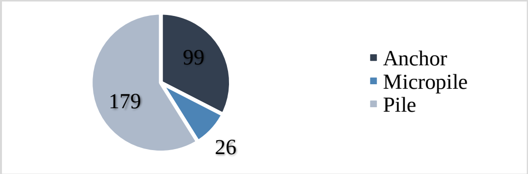


Fig. 6. The number of papers presented about each of the helical members from 1991 to 2020 [1, 7-9, 11-298]

4. The advancement trend of helical anchors

It is better to investigate the research conducted during the period under consideration to determine the expansion and development of helical anchors (Fig. 7). In this way, the issue of the expansion or non-expansion of the helical anchor method and the increase or decrease of research conducted in this field is determined. As shown in Fig. 7 and using the linear trend line, the application of helical anchors in the evaluated time range has a growing trend, and research works in this area are still in progress.

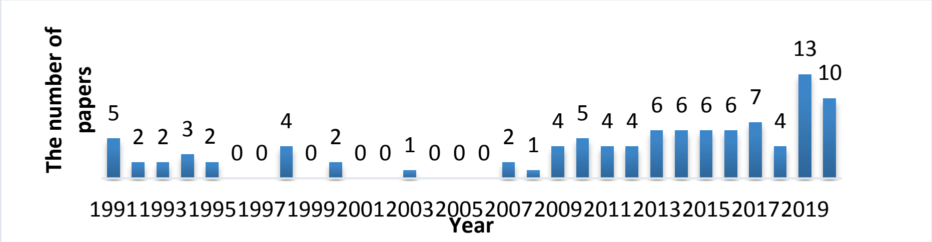


Fig. 7. The number of papers presented about the helical anchor from 1991 to 2020 [1, 7-9, 11-298]

In 1991, the research conducted by Ghaly et al. was entirely in the field of the helical anchor [13-17]. As previously mentioned, helical soil nails are also classified in this group. On the other hand, one of the areas where the helical anchors have much application, but there are very limited research works in this field, is the application of these members for stabilizing walls and slopes. One of the first research works in this field was carried out by Deardorff et al. They have conducted field research about the helical soil nail wall and its construction and design [1]. In another study, Perko has proposed an engineering analysis of the helical anchor capacity and an example of the design of the retaining wall stabilized by this method [5]. Tokhi et al., Sharma et al. and Mahmoudi-Mehrizi et al. carried out three new research works on this method and a pullout test of the screw nail in sand soil [163, 164, 200, 293]. This is one of the areas that require more research and is further discussed in the following sections.

5. The advancement trend of the helical piles and micropiles

The research process on helical piles is presented in Fig. 8. This graph shows that research on helical piles has a growing trend. Increasing the power of equipment and technological progress makes it possible to place high-capacity piles in less accessible areas.

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The advancement trend of the helical micropile method is also evaluated in Fig. 9. In 2000, for the first time, Vickars and Clemence introduced the helical micropile method [8]. In their research, the disadvantages and advantages of this method are described and the field performance of this emerging method is presented. After that, in 2005, Laefer et al. investigated the effect of the grout area on the helical piers [54].

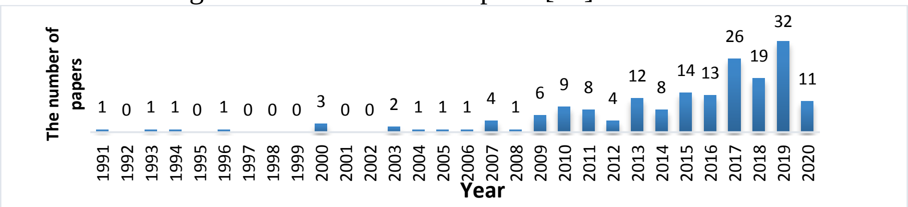

Fig. 8. The number of papers presented about the helical pile from 1991 to 2020 [1, 7-9, 11-298]

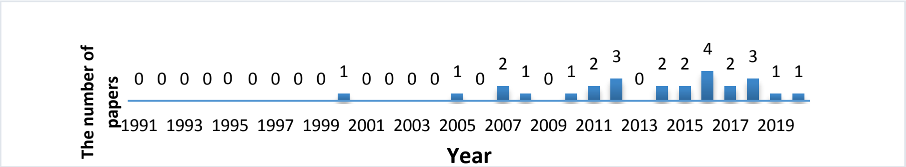

Fig. 9. The number of papers presented about the helical micropile from 1991 to 2020 [1, 7-9, 11-298]

Also, in 24 other papers, extensive research has been done on this method. One of the most important papers is based on the research conducted by Sharnouby and Naggar [20, 56, 57, 88]. They tested the uniform and cyclic axial function of helical piles with grouted shafts reinforced with steel fibers in real-scale. Also, in 2014, Papadopoulos et al. were the first research team who modeled helical micropiles with a three-dimensional finite element program [59]. In their research, Santos Filho et al. investigated the use of grout injection in various conditions to increase the bearing capacity of helical anchors. In a field study, they created holes on an anchor shaft and a top plate welded on the anchor for passing grout [232]. The use of grout in different parts of the helical foundation is one of the areas that need further research and seems to help extend the application of the helical foundations.

6. The type of study soil

By reviewing all the collected papers, it has been attempted to identify the soil type. The purpose of this work is to answer the question of whether helical foundations are used on a particular soil. In Fig. 10, the number of

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studies performed on each soil is specified. Granular, sand and cohesionless soils are classified in the group of cohesionless soils and clay, silt, cohesive, expansive, and swelling soils in the group of cohesive soils. As before, some papers are related to both topics, so the total number of research done in both soil types is more than the number of papers reviewed.

Fig. 10 shows that helical foundations are used in both cohesive and cohesionless soils and reflect the frequent use of this technology. In the conducted research, the cohesionless soils are used more than cohesive soils (about 45%). This has several reasons: The convenience of conducting lab experiments on cohesionless soils, the rapid settlement, and saturation of the cohesionless soils, and having simpler behavioral models, are only some reasons for using this type of soil. In a study conducted by Clemence and Lutenegger, it was found that the contractors, after they fill, have used the clay soils and sand soils respectively in the helical foundations [7]. Finally, it can be noted that helical members are used in both soil types.

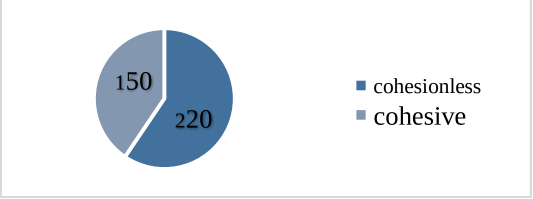

Fig. 10. The number of research done about the helical foundation on any soil type from 1991 to 2020 [1, 7-9, 11-298]

7. The type of study

Another important issue is the type of study done in each research. The purpose is to identify research domains about the helical foundations. In Fig. 11, four groups have been identified and the number of research carried out in each area is specified. The larger number of research works was field research. All field studies, case histories, case studies, and in situ tests are in this group. A large number of performed fieldworks indicate the acceptance and feasibility of this technology. Nevertheless, some countries do not even have an actual implementation of this technology. Laboratory studies and field research also have almost equal numbers. The sum of these studies is also more than the number of papers. Because in 79 papers more than one type of research has been done.

For example, Ghaly et al. in many studies, after performing laboratory experiments, also analyzed the process and presented their analytical models [13, 15-17, 23], or in many laboratory studies, numerical modeling is used for verifying the results [47, 72]. It should be noted that from 1991 to 2020, numerical modeling and field research has been expanded but theoretical studies have been reduced. This is due to the acceptance of this method, the development of operational equipment, the ease of work and cost reduction with numerical modeling, the identification of the theoretical basis of this method, etc.

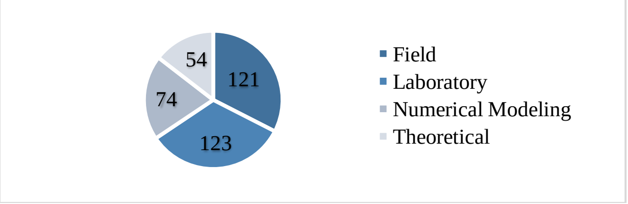

Fig. 11. The number and type of research carried out about the helical member from 1991 to 2020 [1, 7-9, 11-298]

There are some questions regarding numerical modeling. The first question is: which software is used for numerical modeling and which of them is used more than others in the research works? In Fig. 12, the software used and the number of research works conducted with each software are presented. There are a total of 84 works which are more than papers in which numerical modeling is used (74 papers). This is due to the research done by Doust, which, in addition to the FLAC software, provides some explanations for the Magnum FlyT2.0, MDRS, and HelixPro software programs [177]. Akl et al, Sharnouby, and Naggar also respectively used Plaxis, LPILE, Abaqus, and LPILE software programs, simultaneously [189, 233, 251, 252, 271].

As shown in Fig. 12, Abaqus and Plaxis software programs have been most used in helical foundation modeling. In general, software programs based on finite element methods more than finite difference methods or codes of particle methods such as the material point method are used in helical foundation modeling [181]. For familiarization with the helical foundation modeling using Abaqus, Plaxis, FLAC, and MIDAS software programs, respectively the studies conducted by Merifield [21], Rawat and Gupta [190], Pérez et al. [218], and Polishchuk and Maksimov [207] have provided the proper information for readers.

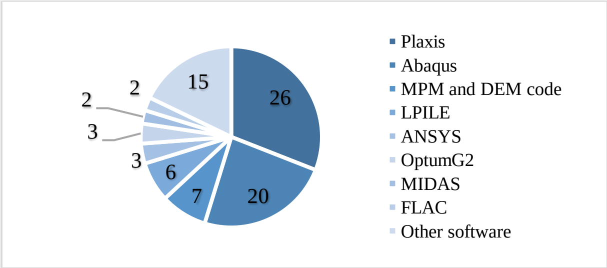

Fig. 12. The number of research works carried out using the types of software programs about the helical foundation from 1991 to 2020 [1, 7-9, 11-298]

The other question about modeling is usually a type of modeling (two-dimensional or three-dimensional?). As shown in Fig. 3, almost both types of modeling have been used for helical foundations. Over time, three-dimensional modeling has been further developed to better understand and predict the behavior of helical anchors and piles [20, 187, 194, 206], but two-dimensional modeling is also used [133, 201].

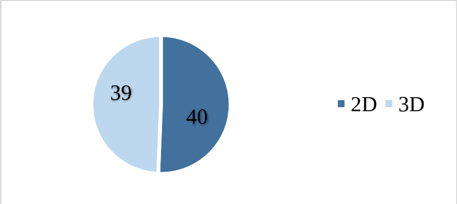

Fig. 13. The number and type of modeling [1, 7-9, 11-298]

8. The number of helices

In 292 collected papers, the number of helical members used has been evaluated (Fig. 14). In many papers, several types of helical anchors and piles have been used, so their total number is more than the number of papers. The helices are spaced apart along the length of the shaft, at a distance of an average of three helical diameters. Due to this spacing and the limited installation torque, the number of helices is usually not more than 4 or 5. The research reviews also show that in 207 papers, a single plate has been used with the helical anchor, pile, or micropile. Subsequently, further research has been done on two-plate helical foundations. Few papers have covered more than 4-helices foundations. This type of helical foundation has special applications such as helical soil nails, which are mentioned in the introduction section.

In 19 papers multi-plate anchor or pile is used, but the number of plates is not mentioned. Therefore, the term "Multi" is used at the end of the graph. In general, and as shown in Fig. 14, in most studies, the multi-plate anchor is used. In the research conducted by Clemence and Lutenegge, the helical foundation contractors have said that they are more likely to use multi-plate helical anchors and piles [7], which is due to the more bearing capacity of these anchors and piles than others. As a result, designers and contractors, by increasing the number of helices, reduce the number of anchors and piles, and reduce costs and increase the project execution speed.

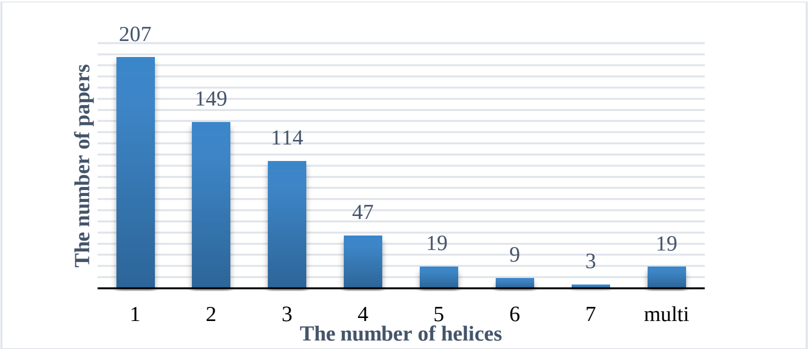

Fig. 14. The number of research done with the different number of helices [1, 7-9, 11-298]

9. The loading type

There are two types of reviews in this section. At first, the works are evaluated in two static and dynamic domains. The reason for this study is to determine the performance of the helical foundations under dynamic loads. This is one of the issues that there are many questions about it. In research conducted by Clemence and Lutenegger, it is also identified that investigating the effect of dynamic and seismic loads on the bearing capacity of helical foundations is one of the issues that is required more research [7]. In 45 out of 292 research papers, dynamic, cyclic or seismic loads have been used. In these papers, various factors such as soil type, the anchor deformation, dynamic loading conditions including time, period, frequency, amplitude, etc, on helical foundation capacity and its displacement are evaluated.

One of the first research works in this field was carried out by Prasad and Rao [119]. They investigated the pullout behavior of helical piles under lateral cyclic loading in clay in a lab study. In another field study, Cannon conducted dynamic loading tests on helical piles of different sizes and lengths under different ground conditions [162]. Also, several recent works were conducted by Wheeler et al, Elkasabgy and Naggar, and Schiavon et al. [213, 217, 219, 233]. Wheeler et al. have studied the reinforcement of railroad tracks on peat soil. This is done by helical piles, to reduce the amount of rail displacement due to the passage of the train [213]. Elkasabgy and Naggar studied the effect of lateral vibration on helical piles in clay [217]. Schiavon et al. also developed a centrifuge modeling of helical anchors under various cyclic loading in sand soils [219].

The lateral resistance of helical anchors and piles is another issue that the contractors and designers of helical foundations have dealt with. Clemence and Lutenegger have also mentioned this issue in their research [7]. Many researchers have done a lot of research to confirm the performance of helical anchors and piles under static and dynamic lateral loads. 49 out of total papers reviewed have examined the impact of lateral force. As mentioned, one of the first research works in this area was conducted by Prasad and Rao. They investigated the pullout behavior of helical piles in clay under lateral cyclic and monotonic loads in a laboratory and theoretical studies [119, 136]. One of the most recent works in this area is the study done by Wey et al. On a field study, they conducted a lateral and axial loading test of helical piles to confirm the design capacity [19]. In another research, Fahmy and Naggar studied the performance of helical piles under axial and lateral loads in clay using 3D numerical modeling [188].

10. The anchor and pile group

The last topic studied in this area is the impact of the anchor and pile group. There are also ambiguities in this issue, and it is not specified in what circumstances, group effects should be taken into account. In the section of the proposed topic for future research, the need for attention to this topic has been emphasized. The first research on the anchor group has been conducted by Ghaly and Hanna research. They conducted laboratory and theoretical studies to analyze the limit equilibrium of single and group performance of the vertical screw anchors, installed in dense, medium, and loose sand. The anchors used in various layouts and deep and shallow conditions were tested. They measured the total pullout load, the pullout load of individual anchors, the upward displacement, sand surface deflection, and the stress developed in the sand layer at all stages of the test [125, 229]. In the same period, Shaheen and Demars investigated the mutual interaction of single anchors in multi-helical anchor groups in granular soils using laboratory and field pullout tests [26].

In the past five years, much research has been done on helical anchor and pile groups. Sakr et al. investigated the uplift capacity of a typical helical pile group with grouted shafts in dry sand in laboratory studies [165]. Ghosh and Samal investigated the mutual interaction of the helical

Table 1. Research conducted on the helical pile and anchor group

Row	Author	Soil type[a]	Plate numbers	Anchor/ pile length	Plate diameter	Anchor/ pile distance	Number of anchors/ piles in group and type of layout[b]
1	Ghaly and Hanna [125]	s	1	200- 400- 600- 800mm	50mm	2D– 4D- 5D	1*3,t- 2*2,s- 2*3,r-3*3,s
2	Hanna and Ghaly [229]	s	1	200- 400- 600- 800mm	50mm	3D– 4D- 5D	1*3,t- 2*2,s- 2*3,r-3*3,s
3	Shaheen and Demars [26]	s	1	18-38 inch	3-6 inch	1D to 5D	1*2,r- 1*3,r- 1*4,r- 1*5,r- 1*3,t- 1*4,t
4	Pack [13]	c-s	2	7.6- 9.1m	203- 254mm	$3D_{max}$	1*3,r
5	Elsherbiny and Naggar [161]	c-s	1-2-3	3.2- 5.5- 5.6- 7.2 m	406- 508- 610mm	2D to 10D	1*2,r- 2*2,s
6	Mittal and Mukherjee [45, 49]	s	1-2-3	200mm	50mm	2.5D	1*2,r- 1*3,t- 2*2,s
7	Dong and Zheng [135]	c-s	3	5m	0.65m	2D	1*3,t
8	Mittal and Mukherjee [51]	s	1-2-3	200mm	50mm	2.5D	1*2,r- 1*3,t- 2*2,s
9	Sakr et al. [165]	s	2	700mm	63mm	4D	1*2,r- 1*3,t- 2*2,s
10	Muthukumar and Shukla [199]	c	1-2-3	200mm	40mm	-	1*2,r- 1*3,t
11	Ghosh and Samal [202]	c	1-2-3	6.25- 7.45- 8.65- 9.85m	2.4 m	1D to 6D	1*2,r- 2*2,s
12	Albusoda and Abbase [204]	c	1-2	150-200-300 mm	15-20 mm	3D– 4D- 5D	2*2,s
13	Lanyi-Bennett and Deng [210]	c	2	6.1 m	305mm	2D– 3D- 5D	2*2,s
14	Lutenegger [225]	c	1	6.1 m- 3.0 m	203- 406mm	1.5D- 2D- 3D- 4D	2*2,s
15	Arsyad and Ratu [228]	p	2-3-4-5-6	5m	600- 800- 1000- 1200 -1400- 1600-1800- 2000 mm	-	2 to 25
16	Al-Busoda and Abbase [234]	c-s	3	30cm	113mm	4.4D- 6.6D- 13.3D	2*2,s- 3*3,s- 4*4,s
17	Dib et al. [286]	c	1-2-4-6	8.2 m	914mm	3D– 4D- 5D	1*2,r
18	Bak et al. [291]	s	3	750mm	100mm	1.5D– 2.5D- 3D-4.5D– 6D- 8D	1*3,t
19	Mahmoudi-Mehrizi et al. [244]	s	1-2-3	375mm	25-30 mm	3D	Hexagon with an anchor in the center
20	Mahmoudi-Mehrizi and Jalali-Moghadam [292]	s	1-2-3	375mm	30mm	4D- 5D	2*2,s- 2*2,s with an anchor in the center

[a] sand=s, clay=c, p=peat
[b] rectangular=r, triangular=t, square=s

anchor group in cohesive soils using finite element analysis [202]. Albusoda and Abbasi conducted a laboratory study and evaluated the performance of single and group helical piles in expansive soil [204]. Lanyi-Bennett and Deng performed a field study in Edmonton, Canada, by axial load testing of single and group helical piles in Glaciolacustrine clay [210]. In a field study, Lautenegger conducted an axial uplift test on the helical anchor group implemented in stiff and soft clay to understand the behavior of the anchor group [225]. Arsyad and Ratu investigated the effect of helical pile foundations on elastic and consolidation settlements in a particular type of peat soil. Al-Busoda and Abbase have studied three-dimensional modeling of soil swelling under the communication towers and used the helical pile group to solve the problems surrounding it [234]. n these studies, parameters such as the length of anchor/ pile, plate diameter, number of plates, the spacing of anchors/ piles, type of layout, and their impact on group effects have been evaluated. Table 1 shows a comparison between the conducted works.

The investigation of the expansion and progress of the technology in Developing Countries

As mentioned previously, the technology of helical members has many applications in soil types and is accepted by many international and domestic regulations. On the other hand, research reviews from 1991 to 2020 show that investigations on helical members have developed and many research works have been conducted in all continents and more than 29 different countries. Now some questions arise: Why in some countries this technology has not been implemented? Are there alternative methods that are more practical, or does the soil type of the project site is effective in the selection or non-selection of this technology? To answer all these questions, a questionnaire has been provided and sent to the individuals involved with this research. In this questionnaire, 30 questions are designed, and, using its results, the reasons for the lack of progress in this technology in a regional and global context are evaluated.

A total of 288 questionnaires were sent to 159 university professors, 8 scientific associations, 121 designers, consultants or contractors of geotechnical projects, and manufacturers of building materials and equipment related to geotechnical projects in Iran. A total of 91 questionnaires were returned (less than one-third of the questionnaires were sent). The first question was about the most important activities in design / consulting / implementation. The highest score in answering the questions

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was 10 and the lowest was 0, and the possibility of giving an equal score existed. The mean score given to each item is presented in Table 2. As it is clear, most of the projects done were site investigation and in situ tests. The reason for this is the need to conduct site investigation in other projects presented in Table 2 or not presented in Table 2, such as the construction of structures, roads, and bridges. The highest score of this item is due to the large number of projects requiring initial studies, the very low cost of conducting studies, cheap equipment, and the existence of many companies having this competence and ability.

It was anticipated that considering the expansion of construction in developing countries such as Iran, the construction of new building foundations would be ranked in the second position. However, since its construction is carried out by construction manager companies, unfortunately, this project has not been implemented by geotechnical designers and contractors. Therefore, this item doesn't have a high score. In many cases, this leads to the improper design and implementation of foundations of structures. The expansion of roads, increasing construction and excavations, the implementation of subsurface projects such as subway lines, facilities, water and wastewater pipelines, and the need for implementation of these projects by the specialists, would increase the need for stabilizing the walls and slopes. So, this item ranked in the second position after site investigation. Reducing the need for dams and the lack of progress in onshore and offshore structures has led to a low score in these sectors.

A large part of the projects was carried out in three sections of the excavation/stabilization of walls, slopes, and retaining walls; ground improvement using grouting and micropiles; and the construction of a new building foundation; in which the helical members can be used directly or as replacement of the injection and micropile methods. On the other hand, in a study conducted by Clemence and Lutenegger, it has also been found that the most common use of helical members is in underpinning for excavation, upgrading new foundations, improving the old foundations, tiebacks, and lateral earth support [7]. Helical anchors and piles also have many applications in onshore and offshore structures, and their expansion can play a significant role in the development of onshore and offshore projects. With all of these applications, helical anchors and piles have not yet found their place in developing countries.

To investigate the possibility of using helical foundations in designed or implemented projects, respondents were asked to rate the number of projects carried out in each soil. The highest score was for remolded and organic soils, meaning that the largest number of projects were done in this type of soil. Subsequently, problematic soils (swelling soils, expansive soils, dispersive soils, etc.) have the largest number of projects. The conditions and the number of projects carried out in other soils are listed in Table 3. Helical anchors and piles can be used in organic and remolded soils, many problematic soils, soft sand and clay, and contaminated soils that constitute a large part of the soils involved in the projects. The study conducted by Clemence and Lutenegger shows that the implementation of the helical foundations in fills, soft and hard/stiff clays, loose and dense sand, and organic soils are most common [7].

Table 2. The score for the most active projects (the highest score is 10 and the lowest is 0)

Site investigation and in situ tests	7.2	Excavation/stabilization of walls, slopes, and retaining walls	6.9
Ground improvement using grouting and micropiles	4.1	Construction of a new building foundation	3.7
Compaction and stone column	3.5	Stabilization, shallow and deep soil mixing	2.6
Tunneling	2.4	Repairing, modifying, and upgrading existing foundation	2.3
Damming	1.9	Onshore and offshore structures	1.3
Transmission pipeline anchoring	0.8	Transmission towers anchoring	0.3

Table 3. The score for the number of projects carried out in each soil type (the highest score is 10 and the lowest is 0)

Remolded and organic soils	7.7	Problematic soils	5.6
Dense or cemented sand	5.5	Soft clay	4.8
Loose sand	4.4	Gravely, rocky soil	4.3
Hard clay	3.6	Rock	3.2
Contaminated soil	2.7	Others	2.1

The next question is related to the subject discussed, and the respondents were asked if they had heard the name of the helical anchors and piles in the past? 75 respondents answered "yes". In the next question, respondents were asked: "In which section, this technology was introduced to you?" 68 respondents, selected this answer: "at conferences, articles, and books". Seven respondents claimed that they have investigated this technology, and none of the respondents have been a designer, consultant, or contractor of this technique. In the questionnaire, questions were asked about the type of project done by the helical anchor or pile, the type of soil, software used for design, etc. However, due to the lack of design and implementation of this method in Iran, no response has been received. Because it was likely that many people would not be familiar with this method or have not implemented a project with this technology, then the last three questions of the questionnaire were related to the reasons for not

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expanding this technology and the methods of its development in developing countries.

At first, some questions were asked about the problems of spreading helical piles and tiebacks in civil engineering and developing countries. The results of the questionnaire are presented in Table 4. A big part of the answers was assigned to the unfamiliarity with the applications and benefits of the helical anchor and pile method. In the study conducted by Clemence and Lutenegger [7], also, these points were the main reasons for the non-application of the helical anchor and pile method, indicating that this method is an emerging one. Items such as "material costs are very high and it is not an economic method", "the employers' tendency to non-risk-taking and economic factors", "the preference for using older methods implemented in the past" and "lack of management in the import sector" by obtaining high scores indicating the need for widespread changes in developing countries to apply the helical anchor and pile method.

After identifying barriers to the development and expansion of the helical anchors and piles, it has been asked about ways to expand it in developing countries. As can be seen from the results of Table 5, laboratory and field research, holding seminars and conferences devoted to the subject, has the highest score. Laboratory and field research in this area has been started and is in progress. Other items require more and better interaction with other countries, and maybe that's why they have obtained low scores. Some developing countries that use the experience of more developed countries have a faster rate of growth in this technology.

Table 4. The barriers to the expansion of the helical anchors and piles in developing countries (the highest score is 10 and the lowest is 0)

Unfamiliarity with the applications and opportunities	8.2
misconceptions about the advantage of this technology	7.4
Unfamiliarity with the design of the method	7.3
The material costs are very high and it is not an economic method	7.0
Employers' tendency to non-risk-taking and economic factors	6.9
In the soil conditions of the region cannot be implemented	6.7
The preference for using older methods implemented in the past	6.6
The impression of having a very low bearing capacity	4.7
Hard and difficult installation in rocky areas and the areas covered with cobblestone	4.6
Not authorized by supervisor and consultant	3.5
Lack of progress in various onshore and offshore areas	3.4
Low resistance against lateral loading	3.1
lack of management in the import sector	2.7
Lack of development of installation equipment and machinery	2.5
The confirmation and localization of new technologies in codes and scientific and executive texts is time-consuming	2.2
Others	3.4

Table 5. The expansion ways of helical anchors and piles (highest score is 10 and the lowest is 0)

Laboratory and field research about the subject	9.2
Holding seminars and conferences on the subject	8.6
Obtaining an agency license to represent international companies providing this technology	7.5
Importing equipment and machinery	7.3
Conducting the project with helical members, overseas and jointly with other countries	5.2
Inviting related companies to hold conferences and specialized workshops	4.6
Others	4.8

As the last item, a question has been asked about the subjects which require further research. As shown in Table 6, the case studies for creating regional practice standards have obtained the highest score. This is certainly one of the most important issues for further research, especially in developing countries, but it should be noted that the existence of the two previous questions (items) can contribute to the high scores of this item. Most of the cases cited in Table 7 and their priority in terms of further research, also emphasized by Clemence and Lutenegger [7].

Table 6. Items in the three fields of design/application/performance associated with helical piles/anchors requiring further research (the highest score is 10 and the lowest is 0)

Case studies to create regional practice standards	7.2
The relation between the installation torque and the capacity for different types of soil	6.8
The behavior of the anchor/pile group	6.1
Lateral resistance of helical piles/anchors	5.9
Investigating the effect of soil disturbance	5.9
Long-term deformation/creep	5.7
Investigating the capacity of a large diameter helix and a large shaft effect	4.6
The effect of seismic/dynamic loads on bearing capacity	3.8
Shaft buckling	3.6
Investigating the behavior of helical soil nails and tieback	3.6
Helical grouted pile behavior	2.7
The use of helical piles/anchors in expansive soils	2.5
The down-drag effect of piles	2.1
Corrosion effects	1.7
Others	5.3

The issues required further research

The review of 292 papers and questionnaire results shows that some issues are requiring further research. Some of these issues are listed in Table 6. In the following, the issues that required further research are presented, and doing more extensive research on them is recommended. Some of these issues are being investigated by this research group:

- Field implementation of helical anchors and piles for various purposes such as: Checking the axial and lateral bearing capacity of single and groups of anchors/ piles - Investigating the effect of different layouts and configurations on bearing capacity - Providing a design guide for applying axial and lateral loading - Determining the effect of anchor and pile interaction and their impact distance in the group in the axial and lateral bearing conditions
- Carrying out site investigation along with measuring the bearing capacity of the helical piles and anchors to Determine the relation between installation torque and the bearing capacity of the helical members in different types of soils - Determine the best layouts in a variety of applications, including wall stabilization, implementation of the foundation, to use the maximum capacity of these members.
- Using collected field implementation data for statistical estimation and probabilistic distributions to more accurately predict the behavior of the helical anchors and piles, as well as their reliability and serviceability.
- Predicting the effect of the disturbance due to the implementation of helical members using a variety of particle methods such as the discrete element method or material point method. Also, determining its impact on the bearing capacity of the members and the effective parameters on it by conducting field studies.
- Investigating the temporary application of helical anchors and piles, for example in temporary stabilization of tunnels or mine walls and their reuse in other parts of the project.
- Using various mortars and resins to extend the application of helical micropiles in clay soils, etc. in which Portland cement grout does not work well.
- Investigating the seismic behavior and performance of single or group helical anchor and pile under real dynamic loads, such as earthquakes and explosions, as well as studying its effects such as soil blast-induced liquefaction on helical piles.
- Designing, implementation, and performance evaluation, long-term durability, the corrosion resistance of large diameter helical piles with a very high bearing capacity for applications such as refinery equipment, platforms, towers, and more. Also, investigating the effect of skin friction and end-bearing in this type of pile.
- Long-term monitoring of the instrumented helical anchors and piles with different applications (wall stabilization, transmission towers, etc.)

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in seismic zones to evaluate their time-dependent function as well as the effects of earthquakes.
- Field comparison of helical anchors and piles with other methods, such as micropiles, drilled shafts, driven concrete piles, driven steel piles, grouted anchors, and ... in the same project, in terms of runtime, cost, and performance of the implemented member.
- Investigating the effect of different types of pile caps, the type and the flexibility of helical pile and anchor joints in transferring the applied forces
- Investigating the implementation conditions of longer helical piles and anchors to increase their bearing capacity; as well as examining the machinery, materials, and change in joint types
- Investigating the implementation barriers, including site conditions, installation equipment, and manpower
- Investigating the combination conditions of different methods of soil improvement with helical members such as the combination of grouting or mixing methods with the above method
- Investigating the performance and behavior of helical anchors and piles in environmentally problematic soils such as expansive soils, collapsible soil, organic soils, frozen soil, and so on.

Conclusions

The primary goal is to collect and compile the published papers from 1991 to 2020 and compare them to help clarify the issue and simplify the topic for future research. For this purpose, a questionnaire is presented to examine the reasons for the lack of progress in the technology of helical anchors and piles in developing countries. Finally, the issues that need further investigation are evaluated. The following is a summary of the most important results:

1. In general, by reviewing the process of conducting 292 research studies, it can be argued that research in the field of helical piles, anchors, and micropiles has been expanded and carried out in all continents and in more than 29 different countries.
2. Most of the work done in the field of the helical members is related to the helical piles. It should be stated that helical piles are more applicable than helical anchors and more extensive research has been done on them. Considering the volume of research works done in this field, it is clear that the helical anchors also have a good performance. The

emerging helical micropiles are also developing and progressing, increasingly.

3. The confirmation of the technology of helical members in various codes and its feasibility in both types of cohesionless and cohesive soils is one of the factors that contributed to the development of this technology. The large number of field studies conducted and the modeling of technology by a wide range of commercial and specialized software programs demonstrate the acceptance and feasibility of this technology.
4. Typically, the number of helices used in the helical anchors and piles is limited to 3 to 4 plates and the multi-plate anchors/ piles are used more than single-plate ones. This is due to the high bearing capacity of these anchors and piles. Using multi-plate anchors and piles, it is possible to reduce the number of single-plate anchors and piles. This will reduce the cost and runtime of the project.
5. It has been proven that the application of the helical anchors and piles in a country like Iran with a wide geographical distribution, different habitat conditions, and diverse projects, can reduce runtime and costs. The issues such as lack of familiarity with applications and benefits, misconceptions about the cost-effectiveness of the method, the risk adversity of the employers, and their preference for using older methods implemented in the past, are just some barriers to the expansion of this method in Iran as a representative of the developing countries. Conducting laboratory and field studies, holding seminars and conferences on helical anchors and piles, obtaining an agency license to represent international companies providing this technology, and importing equipment and machinery, are some ways for the expansion and development of this technology in developing countries.
6. It is suggested to consider some issues such as case studies for establishing regional practical standards, the relation between installation torque and bearing capacity for different types of soils, the behavior of the anchor/pile group, long-term monitoring of the instrumented helical anchors and piles, in conducting further research in the field of the helical anchors.

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