MICROPILES: WORLD WIDE EVOLUTION

2019 International Society for Micropiles Lizzi Lecture

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ABSTRACT

The micropile concept originated more than 60 years ago and has evolved through the innovation of contractors, engineers, and academia to become a well understood tool in the deep foundation toolbox. For a few contractors, initial implementations of micropiles were a strategic tool that allowed them to open doors and solve some difficult challenges. As the awareness grew, the usefulness grew, as did the capacities of each element. Growth also gained the attention of the equipment and tooling manufacturers that met the demands of these unique applications and as such, the industry grew further. The final leg of the stool was to gain uniform acceptance in the design community and this was achieved through several large and small research efforts and the coordinated focus of professional societies and individuals to promote uniform standards. Involvement in this industry for more than 25 years has allowed this author to be a part of much of this evolution and this paper provides reflection of those experiences and a view of the state of the industry at this time.

INTRODUCTION

Fernando Lizzi was the grandfather of the micropile technology and reminds us that "in the field of foundation piling direct experience precedes design." With this philosophy, the International Society for Micropiles was essentially founded September 26, 1997, in Seattle, Washington, by bringing experience together with need following the 1995 Great Hanshin (Kobe) earthquake. However, this meeting of industry leaders was only a milestone in years of efforts by some significant figures in our industry: Donald Bruce, Al DiMillio, Roger Frank, Francois Schlosser, Professor Hoshiya, and Tom Armour, among many others. Mr. DiMillio provided a nice summary of the events leading up to this first workshop in his introductory remarks, available on the ISM website. In this summary, the international relationships built between FHWA and France on the soil nail research project that lead to the FOREVER (FOundations REinforced VERtically) were cited as a foundation for positive cooperation advancing new technologies. This was the model for the international relationship, fostered by Dr. Bruce with Japan, that led to the first workshop.

Efforts to develop a State of the Practice document (Nicholson Construction Company project funded through FHWA) engaged an international panel of reviewers, each with unique insights and opinions about what should be in this document. After three extensive revisions, the document was finally completed and published in 1997, and relationships were solidified that brought many of these experts to this workshop, including the likes of Mike Turner, James Mason, Thomas Herbst, Jouko Lehtonen, Fred Kulhawy, and Paul Groneck. A practical application manual was also being developed by Tom Armour and Ron Chassie of DBM Construction that became the *FHWA Micropile – Design and*

Construction Guideline, 1997: the first generally accepted reference document for implementation of the technology.

The 2nd International Workshop on Micropiles was held in Ube, Japan, in 1999 where the continued collegial relationships grew, and significant research and case histories were summarized. Based on the proceedings, this also engaged numerous contractors, academic institutions, equipment suppliers, and several designers. We must thank Jiro Fukui, Masao Sagara, and Kenichi Kimura as some of the key drivers behind early workshops.

The third event in Turku, Finland, produced some great stories, but was also the beginning of visits from several more longtime friends of the industry, including: Paul Woodfield, Ernst Ischebeck, Pasi Korkeakoski, Gary Weinstein, Bob Traylor, Sami Eronen, and Horst Aschenbroich.

I was first invited to the strategic meeting in Lille, France, in 2001 where a formal mission and vision for ISM was established. This led to the celebration in 2002 of the 50th anniversary of Dr. Lizzi's contributions hosted by Renato Fiorotto in Venice.

IWM 2002 Venice, delegates in Palazzo Pesario Papafava

Figure 1. Photo – IWM 2002 Venice, Delegates in Palazzo Pesario Papafava.

The circle was closed in 2003 in Seattle when our colleagues from Japan presented the two-volume set of design guidance developed through their internal research and the ISM collaborations: *Design and Construction Manual of Seismic Retrofitting of Structural Foundation (Part 1 Design, Part 2 Construction)* by Mr. Ubebara and Mr. Itani.

The list of ISM workshops, and their proceedings and accomplishments are impressive:

1st International Workshop on Micropiles, Seattle, WA 1997
2nd International Workshop on Micropiles, Ube, Japan 1999
3rd International Workshop on Micropiles, Turku, Finland 2000
4th International Workshop on Micropiles, Venice, Italy 2002
5th International Workshop on Micropiles, Seattle, WA 2003
6th International Workshop on Micropiles, Tokyo, Japan 2004
7th ISM Workshop, Schrobenhausen, Germany 2006
8th ISM Workshop, Toronto, ON, Canada 2007
9th ISM Workshop, London, England, UK 2009
10th ISM Workshop, Washington, DC 2010
11th ISM Workshop, Milan, Italy 2012
12th ISM Workshop, Kraków, Poland 2014
13th ISM Workshop, Vancouver, Canada 2017
14th ISM Workshop, Gold Coast, Australia, 2019

In recognition of his vision, the Lizzi Lecture was established at the 5th ISM workshop in Seattle with the presentation of Dr. James Mason's, "Lizzi's Philosophy. Concepts to Practice." Along with this, a student scholarship was established to recognize a young professional doing research to help advance our field. It is an honor to join my mentors and friends in recognizing the work of Dr. Lizzi and the advancements within the micropile industry.

ADVANCEMENTS

The first workshop closed with the development of a needs assessment for the micropile industry. These included:

- Identification of key *in-situ* test parameters that may govern construction, performance, or composite action
- Continued development of the overburden drilling systems and monitoring while drilling
- Design manuals for QA/QC, materials, and load testing, as well as development of design and construction codes
- Design understanding for seismic performance and ground improvement applications; testing and advancement of Case 2 systems
- Evaluate all non-destructive testing methods for load verification
- Continuation of regular workshops to advance the practice

A brief history of micropile development in North America following the 1952 patent by Fondedile in Italy includes (ISM workshop references are noted as [ ]):

1970 Fondedile Corp established in the U.S. [Bares, 2007]
1972 First use of Root Piles in U.S. (Illinois)
1973 First use of Root Piles in Canada (Montreal, Longoeuil subway station)
1973 First tangent micropile anchored retaining wall and WMATA project underpinning in the US (Glen Burnie, MD)

1977 First use of Root Piles for Slope Stabilization, Forest Highway 7 (FHWA, Mendocino, CA)
Late 1970s Protective patents run out and first use by anchor/drilling contractors (Nicholson, Dywidag)
1979 The last reticulated micropile wall constructed in U.S. by Fondedile (Monessen, PA)
1980-1990 Decline and closure of Fondedile in U.S.
Early 1980s Big "push" by east coast contractors
1980 Linn Cove Viaduct, Blue Ridge Pkwy [Siel, 2006]
1984 First "Type A" wall for slope stability (Armstrong, Pennsylvania)
1985 CP Rail Viaduct at Roger's Pass, BC [Lie & Kast, 2007]
1989 Loma Prieta and start of micropile market for seismic retrofit on the West Coast.
Mid-1990s "Split" of original Nicholson team, stimulates growth on West Coast (DBM, NWC) and East/South (Hayward Baker, SPS, Layne, Moretrench, et al.)
Late 1990s Expansion of the technology

Williamsburg Bridge, NYC (1996-1998)
Engle Machine, York, PA; I78 over Delaware River; SR 4023 Armstrong County Slope Stabilization
Mandalay Bay, Las Vegas (1998) [Vanderpool, 2002]
Exton Square Mall, Exton, PA (1999)
U.S. Marines Research Project – Baltimore, MD (1999) [Bruce & Weinstein, 2002]

New Millennium

Spallation Neutron Source, Oak Ridge, TN (2001)
Richmond-San Rafael Project, CA (2000-2003) [Hadzariga, 2002]
"Macropiles" (Long Island, Queens, NY, Mid-2005) [Wolosick, 2006]
Big Qualicum Bridge, BC (2006) [Li & Kast, 2007]
NJ Turnpike Hollow Bar Micropiles [Gomez, 2007]
Underpin 1000 yr old tree [Aschenbroich, 2010]
Sunrise Power Link – First ISM World Cup winner [Salisbury & Davidow, 2014]

The shared record of these projects by the members of ISM and many other contributors has helped advance the state of the practice, technical understanding, and education of the community throughout the world at a much faster rate than most other technologies introduced to our profession.

As we review these cases and many others and reflect on the presentation of colleagues such as Dr. Bruce, John Wolosick, Tom Armour, and Tom Richards, among others, we can trace the rapid advancement of the technology. Advancements occurred in reliability as demonstrated by the rapid design capacity increase through the 1980s and 1990s. Typical, lightly loaded elements designed by Dr. Lizzi and Fondidele, ranging from about 10 to 20 tons, were readily supplanted with new materials and larger drilling capabilities to regularly achieve working loads in excess of 100 to 200 tons. Milestone projects, such as the Richmond San Rafael Bridge, tests at Hardefeldt Airport, and "macropiles" in New York, demonstrated capacities well in excess of 700 to 1000 tons by the turn of the millennium. Here in Australia, Barilla [2019] reported on a load test demonstrating more than 1,600 tons in an argillite rock socket.

Advancements of fundamental understanding of how micropiles functioned and development of accepted design methodologies were a significant key to the rapid evolution. These advancements were led by the contractors marketing a value-added product to their clients as Dr. Lizzi demonstrated with Fondedile in Italy. By understanding the performance of this tool, contractors are able to identify suitable applications and sell a solution. However, as Dr. Lizzi pointed out, although direct experience precedes design "in some instances we designed "Reticulated Root Piles" structure with positive exuberance" [Bares, 2007]. Bringing a new technology to market on a larger scale required more than exuberance to convince owners and public agencies that it is a widely accepted method. Further, without acceptable standards, dissuasive arguments were readily made by competitors in the market.

In the early days (1970s), the fact that the design was geared to generate a factor of safety based on individual experience and not on hard numbers makes less experienced U.S. engineers wary" [Bares, 2007]. This need for acceptance led the research effort to move from the contractors and material suppliers to the general mass of universities, public agency funding, and professional society groups. Bruce, in his 2006 Schrobenhausen presentation*, An Education in Micropiles: The Expansion of the Market in North America,* highlighted the impact of various groups that he cited as "The U.S. Model" of industry advancement.

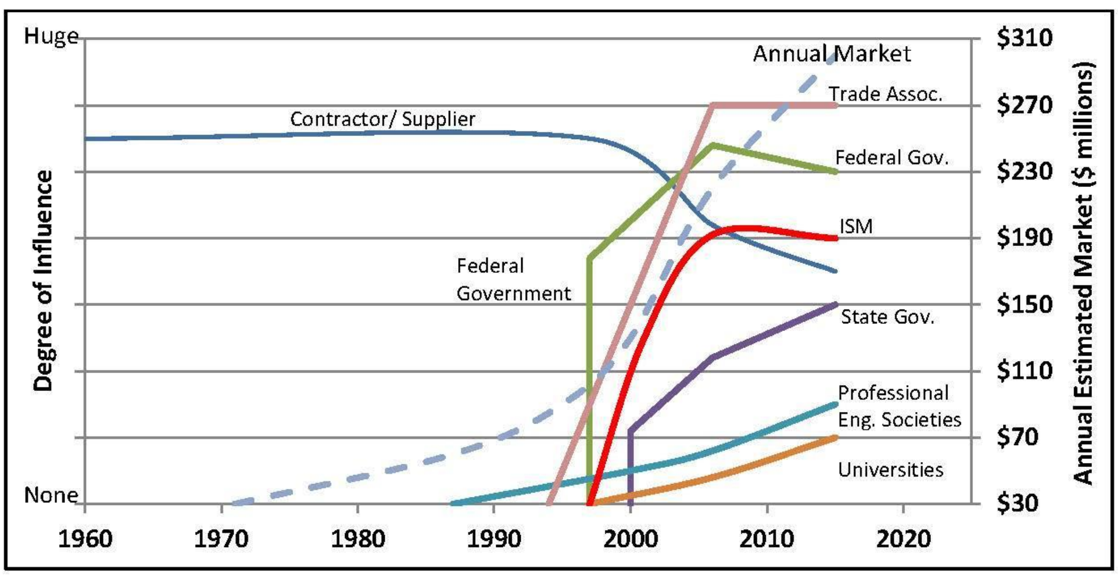

Figure 2. The U.S. model, after Bruce [2006].

This is not unique to the U.S. and has been replicated in various forms around the world. Examples such as FOREVER and JAMP highlight cooperative research efforts that led to significant advancements. Further, the ISM education tours, and support by Mark Hinton and Paul Woodfield of Branlow Construction in the U.K. and Alan Herse and

Robert Bollman of PCA Ground Engineering in Australia made great strides to build confidence in micropiles across their local market.

Figure 3. Photo – ISM “Educators” during UK teaching tour.

Some of the key research efforts answered tough questions related to retrofit of structures for seismic load cases, group effects and reticulation benefits, buckling of slender elements, effects of repeated loading cycles, strain compatibility, grout behavior, load testing method, etc., and helped define the accepted standards that led to the creation of common building code sections around the world.

Only through combined efforts can true technology advancements occur. Consensus drives adoption and can only be achieved through dissemination of knowledge and resolution of unknowns. In most areas, this is marked by the adoption of accepted design standards such as Eurocode, AASHTO, IBC, and many others that, through the efforts of dedicated volunteers, now include provisions for micropile design and construction.

EQUIPMENT AND TOOLING

One of the greatest drivers in the advance of the micropile technology lies in the materials and equipment revolution. Bares noted that the first jobs brought to light the “operational problems that will continuously plague the growth of the Company in the US. The M1 rigs sent to the US require a crew larger than the more modern rigs would in a country where labor is four times more expensive than in Italy. They are powered by electric motors, a common feature in Italy (where fuel cost is four times higher than in the US) thus requiring generators and additional labor.” This was also one of the key factors in contractors beginning to leave drill casing in the ground as the cost of labor to remove the material was greater than the savings of reuse. When the contractors realized the casing would remain, they quickly began to take advantage of the extra reinforcing in the design calculations. Numerous examples of equipment, tooling and materials advancement demonstrate how the industry has responded to the needs of the market.

In 2000, Armour presented a summary of the various tooling/drilling methods available at the time for micropile installation.

Table 1. Available Tooling/Drilling Methods (Armour, 2000).

Drilling Method	Principle	Common Diameters And Depths	Notes
Single-tube advancement a) Drive drilling b) External flush	Casing with “lost point” percussed without flush. Casing, with shoe, rotated with strong water flush.	50–100 mm to 30 m 100–250 mm to 60 m	Obstructions or very dense soil problematical. Very common for anchor installation. Needs high torque head and powerful flush pump.
2. Rotary duplex	Simultaneous rotation and advancement of casing plus internal rod, carrying flush.	110–220 mm to 70 m	Used only in very sensitive soil/site conditions. Needs positive flush return. Needs high torques. (Internal flushing only.)
Rotary percussive concentric duplex	As 2 above, except casing and rods percussed as well as rotated.	89–175 mm to 40 m	Useful in obstructed/ rocky conditions. Needs powerful top rotary percussive hammer.
Rotary percussive eccentric duplex	As 2, except eccentric bit on rod cuts oversized hole to ease casing advance.	89–200 mm to 60 m	Expensive and difficult system for difficult overburden.
“Double head” duplex	As 2 or 3, except casing and rods may rotate in opposite directions.	100–150 mm to 60 m	Powerful, new system for fast, straight drilling in very difficult ground. Needs significant hydraulic power.
Hollow-stem auger	Auger rotated to depth to permit subsequent introduction of grout and/or reinforcement through stem.	100–400 to 30 m	Obstruction problematical; care must be exercised in cohesionless soils. Prevents application in higher grout pressures.

As noted in the first Workshop, there was a significant need for advancing overburden drilling systems and monitoring drilling methods. Tooling was generally inefficient in difficult ground conditions which were the highlight of the technology. Further, the methods available often used excessive fluid flush and resulted in more damage to the ground (or existing structures) than could be tolerated. By the beginning of the millennium, tooling had advanced to be much more reliable with the advent of overreaming downhole hammer bits such as the Numa Super Jaws® system, and, more recently, the Center Rock Roto Loc tooling [Bruce, 2017], as well as the growth of the availability of hydraulic drill rigs of various sizes and capacities. With the smallest rigs, the installation could be completed in the tightest confines. With the larger long masts, the cost of a micropile was becoming competitive with alternative systems, often with more reliable installation processes and greater capacity-to-cost ratios.

Economics drive everything in the construction market. Similarly, Fondedile realized this even impacts the grout used in a micropile. Where sanded cement grout (mortar) was traditionally utilized in Italy due to the costs of cement, the labor and equipment costs (wear on the pump components) in the United States and relatively low cement cost resulted in the more efficient use of a neat cement grouting process. Further, the equipment available allowed the pressurizing of the grout during pumping rather than the post grouted application of an air blasting process.

TODAY AND TOMORROW

Survey

I would like to continue this discussion of the advancement of our industry and the state of the practice and market based on some responses from our colleagues. To build on my 2007 presentation in Toronto on the growth of the U.S. market through 2006, I posed some general questions to friends around the world to develop a summary of where we are today, how we got here, and where we might be headed.

I would like to thank my friends around the world who provided some insightful responses, albeit with a little extra prodding in some cases. The responses, 26 representatives, covered each of the five ISM regions (North America, Central/South America, Asia, Europe, Northern Europe). These responses were drawn primarily from past ISM attendance – many of the very familiar faces. The number of responses was somewhat managed by me in an effort to limit redundancy in the major markets but with a goal to get a variety of perspectives. North America is well represented and, as would be expected over such a large area, demonstrated a variety of opinions on many questions.

Maturity of the Industry

Generally, the core ISM markets are mature and in some cases may be slowing the rate of advancement or shifting the way the technology is being implemented. The preponderance of implementation is centered on urban areas with more limited uses in less densely populated areas unless there is a distinct industrial or infrastructure need (transmission towers, large structures over karstic geology, petroleum production in remote areas). As the knowledge and confidence spread along with readily available equipment, the evolution has been to utilize larger and fewer piles. Another trend has been the move to more regular use of hollow bars.

Canada demonstrated this trend with significant work in large metropolitan centers such as Toronto, driven by market demands and very active ISM members. However, the western areas seem to have had a smaller demand and are just now emerging within the market data. This may also be a result of diversification within the contractor base. The U.S. market is mature with well accepted design standards implemented. However, even across the U.S. there are numerous emerging designers and contractors continuing to learn the tools.

South and Central America had a small response and would be considered an emerging market with core areas of some experience and contractors performing the work. There have been several significant project completed in the past decade or two, but the technology is not consistently applied.

Asia is a mixed bag. The Chinese market is emerging; however, it is unclear how micropile applications are being implemented. Within China, there is clearly a significant production market for drilling equipment, tools, and materials. With such numerous large urban centers, the limited access capabilities of micropiles seem to fit. However, urban projects often seem to be redevelopment not adaptation, and thus larger deep foundation systems are employed. Japan is an early adopter in the advancement of the market, as discussed above. Given the controlled implementation model of JAMP, the market would be considered mature and is believed to be steady. South Korea similarly seems to be a controlled implementation and thus may be considered mature; however, the market scale is likely small and thus limited groups share in this expertise. Australia is also a mixed bag, again driven by contractors over limited areas of the country with some significant applications, while other areas may have little or no experience. The small islands of New Zealand have recently become a growing market following their own seismicity concerns and the need to reinforce infrastructure to meet new design codes similar to Japan in the late 90s.

Like all technologies, it is as much of a people industry as a technology. Salesmanship, investment, and experience drive maturity of the marketplaces. If there is not a driving need (Japan seismicity or contractor with a desire), then other technologies continue to fill the space micropiles could fit.

Initiation of the Market

The industry growth has primarily been the result of contractors in most regions. Seeking competitive advantages, new tools are added to their toolbox to allow greater value to be offered to a client. Often, the significant market growth drivers are associated with environmental changes and natural disasters. Fondidele and Dr. Lizzi started a little differently with their economic driver being the destructive effects of a war and the resulting restoration of historic structures or reconstruction of critical infrastructure.

Potentially the greatest driver is seismicity. The U.S., Japan, and now New Zealand and South America can associate significant advancements to the need for reconstruction or retrofitting resulting from earthquake event(s). This driver has likely impacted most developed regions and unfortunately more events will occur and stimulate our market.

Climate changes are another factor in many areas. A drought in the U.K. drove early micropile work in the late 70s. More significantly in Northern European countries where declining groundwater tables have exposed timber piles to degradation, the micropile industry beginning with driven bars then tubular steel products became a rehabilitation trend. Without venturing into a discussion of climate change, it is likely that changes along coastal cities and even inland waterways will have an impact on our industry in the future.

A significant factor in the eastern U.S. market is karstic geologic conditions located in and around urban areas undergoing sprawl which happened to be near specialty contractors interested in the technology. Within a decade or two, there was a clear evolution of the deep foundation market as it transitioned from driven piles and socketed drilled shafts to micropiles for many difficult sites where steeply dipping pinnacles, floating boulders, and caverns existed.

Some of the earliest micropiles (1970s) in Venezuela were done by engineers inserting bars into holes drilled with test boring rigs and continued with a significant landslide curtain built with this method in the 80s. It was not until a large viaduct in Caracas collapsed that a significant project was supported by cased micropiles. This project was completed by Franki South America [Gomez, 2011].
South Korean population growth and housing needs have been their driver because they are not able to tear down structures and rebuild. Therefore, the market for foundation enhancement with micropiles is growing to allow retrofit for seismicity and the ability to add floors to the existing structures.

I presented the value of innovative and entrepreneurial contractors as the first driving force and this is undoubtedly the most significant factor around the world. However, the cooperative university research completed with FOREVER in Europe, the industry research in northern Europe that gained adoption of the steel tubes in micropiles, and the volunteer work in the U.S. by groups within ADSC and DFI did the heavy lifting of gaining adoption through their research, code development, and outreach/education efforts.

Prevalent Applications

We are all familiar with most applications of micropiles and their flexibility to meet difficult challenges for tight access and difficult ground. There have also been some more unique drivers that have resulted in applications of micropiles to less obvious situations including:

Seismic Retrofit – I would be remiss if I didn't begin this section with this presentation. Retrofitting buildings and possibly more impactful, older infrastructure such as bridges and critical lifeline infrastructure may present the most significant revenue opportunities.

Karst – The highly variable conditions are accommodated well with the modular construction of micropiles (casing and bars that are threaded); the capabilities of the drills to penetrate the sloping rock and voids; and the ability to implement grouting for ground improvement when required. However, there have also been challenges created by ground disturbance from drilling and excessive grout injection.

Transmission Towers and Wind Farms – The load combinations of these structures results in significant tension loads. Micropiles are well suited for this and could also be installed in groups potentially taking advantage of reticulation benefits. Locations of these structures are often difficult to access; so difficult that helicopters are used to fly equipment and materials into some sites.

Excavation Support – Contiguous pile walls have been built (most known are those in Europe) where the drilling and grouting process results in a combination of reinforced improved ground that can serve as earth retention, and often is integrated with underpinning of adjacent structures. Early reports of such projects also include Bishop et al. [2009], Borda (2004), and, more recently, Snow [2019].

Uplift resistance – Numerous projects have been reported around the world where floors and bottom mat structures have been tied down with micropiles to resist high groundwater levels (or tidal rise). This can be done during initial construction or, in many cases, as retrofits in below-grade parking structures. Case histories completed under artesian groundwater pressures have been reported [Beirne-Lewis, 2017].

Roadway slope reinforcement – The Australian market seems to have grown significantly based on using A-wall systems to reinforce roadway slopes.

Emergency stabilization – Although a rarity (fortunately), there have been some very significant revenue and technically challenging micropile projects used to mitigate excessive settlement of structures during construction. Examples include the Mandalay Bay project [Vanderpool, 2002] and an office building [Cadden, 2002].

Prevalent Types of Piles

The micropile industry has been innovative and has evolved to apply the technological concepts with available materials to meet the needs of a project. I anticipated responses to the questionnaire about the type of micropiles to follow their lifecycle in the marketplace. I think it is a safe statement to say that there are few areas with a predominant type. Newer markets seem to adopt hollow bar technologies possibly because of availability of equipment and handling advantages for smaller contractors. However, there seems to be some correlation of well-established urban earth retention market contractors with larger rigs and the use of cased piles.

Northern Europe, however, is fairly consistent with their use of tubular steel piles, often designed as end-bearing elements on the hard rock. A similar application is used in the Chicago area in the U.S.

Equipment and Materials

Equipment is readily available throughout our market areas. Equipment of all sizes is provided by numerous manufacturers. Equipment is often European, with some coming from Japan, and specialty equipment coming from other areas like the United States.

China is also currently producing a significant number of rotary drill rigs for the foundation market in Asia. Furthermore, contractors have built their own (or modified) rigs and attachments for micropile installation. Safety criteria for rig operations are beginning to limit the opportunity for contractors to develop rigs when detailed engineering and operation manuals are being required.

Figure 4. Photo – Large long-mast rigs make greenfield applications cost effective.

Figure 5. Photo – Modern equipment for limited access applications.

Bruce (2012) provided a summary of drilling methods indicating that double-head or dual-rotary tooling was used in the most difficult ground condition. Until recently, this equipment was not readily available within the industry and there are many examples of problems completing projects or damage done to ground conditions when holes could not be completed effectively. Double-head configurations are more readily available to some of the larger contractors and are being used more regularly.

Hollow bars have become more readily available which has resulted in expansion of this market. Within the U.S., federally funded projects are required to use steel traceable to mills in the U.S. Until multiple suppliers of bars began to produce this material within the U.S., there were limitations to its use. The ready availability of small (lower cost) drill rigs and attachments specifically made to install hollow bars further expanded their use.

The micropile industry is based on the modular installation of threaded materials. As such, a variety of threaded bars has become available with ever increasing diameters and steel strength. We regularly see No. 20, and occasionally No. 28 bars (2.5- and 3.5-inch diameter). Yield strengths are regularly 75 ksi, with availability of steel grades having minimum yields of 90 to 100 ksi. For tension and occasional compression loads, 150 ksi (ultimate strength) bars are used. Similarly, the hollow bar industry has provided larger size materials, with 208 mm bars introduced at this workshop in Australia [Ischebeck, 2019].

The industry has also seen changes driven by the market. Of particular note have been the fluctuations in the oil drilling industry, where the use of casing has made supply difficult at times. The high capacity micropile market is based on several typical casing sizes: 5½, 7, and 9⅝ inch. When the oil fields are active, the surplus or mill secondary market can be very limited for these sizes. When the oil industry slows down, a glut of this pipe can become available. Thus, there can be significant impacts on the economics of the piles and on the creativity of contractors to use alternative pile sizes and configurations.

DESIGN CODES

Micropiles were late to the game within the modern building codes, and the initial design was based on similar systems in use at the time. Numerous summaries are available in the IWM literature describing the alternative design approaches related to drilled shafts or driven pile systems until the turn of the millennium, when we saw the completion of EuroCode EN 1997 and micropile execution EN14199, and additions to the International Building Code (IBC) and American Association for State Highway and Transportation Officers (AASHTO) design codes. It wasn't until about 2009 when the micropile construction code appeared in AASHTO. Although foundation codes address most considerations, local steel and concrete codes are applied to some components. Often it is the lead designers or the owner's representatives that make final decisions about the appropriateness of a code when conflicts between codes emerge.

Local annex documents are available throughout the world as local experiences are factored into the national (or internationally) accepted standard. This applies to countries outside of the European Union and the U.S. that have adopted the widely accepted standards. This also applies within those entities when countries in the EU have developed Annex documents. Similarly, many states and localities in the United States have addendum documents that make modifications to IBC and AASHTO to fit their local practices or preferences.

Industry-specific documents are appearing more recently. Of note, the electric utility industry seems to be compiling and standardizing guidance for tower structures because these tend to have unique loading and performance issues different from those of buildings and bridges that are the basis of other codes (i.e., Korean Electric Power Corporation [KEPCO, 2017]). Other guidance has been developed for wind turbine towers. Large energy producers such as BC Hydro also have their own code requirements.

Many codes have evolved and are constrained by historic experiences with other foundation systems. As such, the deterministic factors included in these codes can be overly conservative for micropiles and are only now beginning to be addressed. Of note, allowable steel stresses have historically been limited in some codes to account for driving stresses and damage that would not impact micropile capacities.

Again, I would be remiss if I did not include mention of professional societies in the development of micropile codes. Until codes are adopted regionally, industry organizations have often stepped in to provide guidance. Of note was the early micropile DFI/ADSC Joint Micropile Committee's *Guide to Drafting a Specification for Micropiles,* developed over a seven-year period and first printed in 2004, though widely circulated years before.

PROMINENT FIGURES (THE PEOPLE FACTOR)

It has been a true joy to work in this industry as it has evolved and to have had the opportunity to share ideas and build friendships with many of the key visionaries of the micropile industry. Many of these contributors were noted above. Below are a few more people and organizations or contractors (although definitely not a complete list) who were recognized by my colleagues in this survey:

Figure 6. Photo – Donald Bruce, Horst Aschenbroich, and Allen Cadden at IWM 2017, Vancouver.

Figure 7. Photo – Bjorn and Ernst Ischebeck, Robert Soltysiek, and Thomas Herbst.

Ischebeck Corporation A driver in education and research
UK Mike Turner
ermany Wolfgang Brunner
oland Bolek Klosinski – retired IBDiM (Poland Research Institute of Roads and Bridges)
Finland Prof. J. Hartikainen, Mr. J. Lehtonen, and Mr. R. Heikinheimo
orway Bo Berglars, Håkan Bredenberg, Göran Camitz, Ulf Bergdahl, Tor-Gunnar Vinka – Gunnar Holmberg
Sweden Gary Axelsson, Arne Schram Simonsen
Venezuela Antonio Martin – Franki South America
Chile Pilotes Terratest S.A.
nited States Nicholson Construction – everyone seems to have had ties to them in the early days – (Peter Nicholson, Seth Perlman, Spark Johnson, Butch Tripplet) and FHWA Advisory Panel – Jesús Gómez – Williams Form Engineering
anada GeoFoundations – Jim Bruce, Isherwood – Nadir Ansari, and Geopacific Consultants Ltd. – Matt Kokan
Australia Our host, Allan Herse, and Robert Bollman – PCA Ground Engineering
hina Feng Qin developed the micropile and anchor equipment for the Chinese market
orea Changho Choi, Bansuk Foundations Co., ExtPile Co., and the Korea Institute of Construction Technology

TRENDS IN THE MICROPILE INDUSTRY

Twelve years ago in Toronto, I provided a summary of another informal survey and tried to estimate the size of the market in the U.S. at the time. The estimate was based on a market survey ADSC completed at the time and on interviews with colleagues. At that time, the predicted market for micropile construction in the United States and Canada was about $300 million US. The predominance of the work was done in urban centers of the East and West Coasts. Some of the other conclusions included:

- The typical size of projects will remain constant (~$100k to $1M)
- There has been a slight slowing of growth rate in past couple years
- Power Industry and Transportation could result in an increase of Mega Projects
- Equipment and Manpower will be constraints
- Innovative solution growth – Hollow Bars, Sonic
- Increase in smaller contractors to market

The response to the recent survey seems to be consistent with many of these points. Other than consolidation of several mid to larger experienced contractors into the Keller Corporation, many other smaller contractors have diversified into the micropile technology starting up primarily by leveraging the smaller drilling equipment that is readily available and multiple sources for hollow bar material. Although not specifically requested, my opinion is that the predominance of micropile projects remains in the small to mid-size revenue range of $100,000 to $1 Million US.

We continue to see occasional mega micropile projects and the power industry has been a recent leader in applying this technology to some significant transmission tower projects. Other large projects have included industrial developments over difficult terrain, such as karst, and emergency repairs.

Reviewing the response to market sizes, we seem to see a flattening of the market with variable responses in many regions. Annual market sizes reported and estimated from the information provided include:

- European responses were limited and narrowly focused to a country or pile type, but based on this information and the size of the European community, I would suspect the market across Europe exceeds $50 to $100 Million US.
- Northern Europe likely matches or exceeds this value, and a more complete estimate potentially totaling $100 to $150M US was provided by responders.
- The South American market is believed to be small – less than $5M US; however, contractors are beginning to apply the technology to the seismic challenges of the region.
- Central American countries could approach $5 to $10M US.
- The U.S. market predictions varied significantly across this large geographic space, likely dependent on the markets where each responder worked. Estimates generally ranged from about $100 to $300M US with a higher estimate of about $750M US when consideration is given to some very large emergency or infrastructure projects.
- Canada seems to have about $25M in each major urban area, so an estimate of about $75 to $100M would be reasonable for urban areas, with additional revenue being generated again from major power transmission markets.
- Asia – This region is believed to have a high growth potential from emerging economies and seismicity driven demands. Australia is currently estimated at about $20M. China has a huge potential, but is currently believed to be at about

$20M, with a growth rate of 20% anticipated. Korea is challenged to get projects to move ahead and is likely at about $1M US, but is hard to predict because it is all private work.

Although the responses varied again on the trends for revenue growth, few respondents indicated flat or declining trends in the markets. Most respondents believe that the micropile market will continue to grow at between 5 and 15% in their regions. Declining indicators were related to competition from other ground improvement technologies as well as commoditization in some mature markets. Growth factors include high capacity-to-cost ratios, readily available steel in some markets, emerging code changes to adopt the technology and retrofit requirements from seismicity changes and urban growth (particularly for uplift and lateral stability improvement), and acceptance of new materials such as hollow bars for ready installation by emerging contractors.

CONCLUSION

The industry has reached a level of maturity that substantiates well thought out application of the technology. This has facilitated the growth of acceptance in the design community, emergence of new material and tooling to meet the requirements, equipment development specifically for installation of small elements in tight areas, and emergence of a growing number of contractors entering the industry. All of this has produced a steady growth over the past two decades, reaching a global market size that could be approaching $1 Billion US annually, with a continued growth in the neighborhood of 10% per year.

Advancements in the industry are occurring at a slower rate now that we have established procedures and robust supporting technologies. However, there are still limitations and barriers to good micropile industry practices. These include:

- Prescriptive design codes that are built on historic experiences with other types of foundations, rather than the performance-based evidence that we could be developing to craft a more representative design standard.
- Education of new practitioners on both the design and construction side, so we do not continue to relearn lessons of the past.
- Knowledge transfer to emerging markets, again so we do not reinvent the wheel around the globe.
- Continued research into ways to leverage this technology to meet the challenges of today and tomorrow.
- Research (and integration into practice) into better use of micropiles for seismic retrofit, whether it is related to lateral performance, connection details, strain compatibility, group behavior, or the benefits of reticulation.
- Reliability of bond values in various geologies.
- Quality control and testing procedures, including monitoring while drilling, as noted in the earliest IWM meeting, is still needed.

CLOSING

This is a great industry, filled with great people, that I have had the pleasure to be a part of for much of my career. I would like to extend my sincerest gratitude to all of those people noted above, and many others who have allowed me to be a part of their careers as well. I would also like to thank Schnabel Engineering for the incredible support they have provided over the past 30 years to both my participation and to the innovations within the micropile industry over this time. I am looking forward to working with you great people around the world for years to come.

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