Rigid Inclusions: A Spectrum of Applicability

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ABSTRACT

Rigid inclusions (RIs) are no longer a new ground improvement technique. RIs, which are columns typically made of concrete or mortar, are used to reduce settlement and increase bearing capacity. They have been used by many geotechnical engineers, contractors, developers, and owners over the last 30 years. In this paper, we will show that, in fact, they have been used in many forms for centuries. This paper will highlight the wide variety of projects and soils that RIs can be applied to and the associated considerations. Current practice with RIs is in the realm of "ground improvement," where many techniques are used to mitigate settlement and enhance bearing capacity. Projects that require settlement mitigation only tend to attract many techniques, and a technique is chosen based on its overall economic value (constructability, schedule, value, sustainability benefits, etc.). For projects where RIs are used to improve inadequate bearing capacity of the soils, the choices for foundation support become fewer (e.g., piles, drilled shafts, RIs, or soil mixing). The difference between providing settlement control versus increasing bearing capacity is stark, and between them lies a large range of conditions that requires careful consideration. RIs can be used on projects with a large spectrum of conditions, but often jurisdictions, specifications, and project requirements force the design, installation, and testing of the RIs as if they are piles. This significantly limits the amount of optimization and benefit that the RI solution can offer and discounts the advancements that RI technology offers to our industry. This paper will provide a description of the spectrum of conditions that RIs can be applied to and present the different challenges that apply based on those varying conditions. A hypothetical study will be presented that evaluates how RI behavior varies depending on the soil conditions and the primary purpose of the RI system (settlement mitigation or enhancing bearing capacity).

INTRODUCTION

Rigid Inclusions (RIs) are columns that are significantly stiffer than the surrounding soils and mitigate settlement and increase bearing capacity of the soils. RIs are typically installed with a displacement auger or with a vibrated mandrel and ranging from 28 to 45 cm (11 to 18 inches) in diameter. RIs were initially introduced as an alternative to stone columns on ground improvement sites with a layer of soft soil that would not be able to provide sufficient lateral confinement of the stone column through the soft soil (ASIRI, 2012, Masse, 2019). The use of RIs, though, has evolved. This evolution and its impacts are described below from the authors' perspectives. The authors, though aware of common practices industry-wide, are speaking from experience working for a single ground improvement contractor working domestically and around the world.

DESCRIPTION OF THE SPECTRUM OF APPLICABILITY

As they came into use, RIs were typically designed for low axial compressive stresses (approximately 6.5 kPa or 600 psi) and were not considered to impact the footing bearing capacity or the structural design of the footings or slabs the RIs supported. Many of the sites where RIs were used contained a layer of granular fill near the ground surface that provided an adequate factor of safety against a bearing capacity failure. The RIs mitigated settlement and allowed for the use of shallow foundations and slab-on-grade in place of thick, heavily-reinforced pile caps, grade beams, and structural slabs. Load transfer platforms (LTPs), which separated the RIs and the superstructure, were generally made of dense graded aggregate (DGA). The thickness and quality of the LTP, which are a key component of the RI design, were carefully determined and respected. The LTP allows for the load to engage with the in-situ soils, which allows for the optimization of the RI system. As such, the RI systems were highly redundant, providing lower capacities than typical piles and creating a more flexible and redundant system that was not reliant on the performance of any one individual element. Often, RIs were placed on a square grid across a site, independent of where the individual foundation elements were located. See Figure 1 for two different ground improvement layouts – one where we perform global ground improvement across a site and another with targeted at the locations of the loads. Note that in Figure 1a, the red circles indicate additional targeted support; however, that support is provided in the center of a grid to provide additional capacity and redundancy, not directly beneath the more highly loaded foundation.

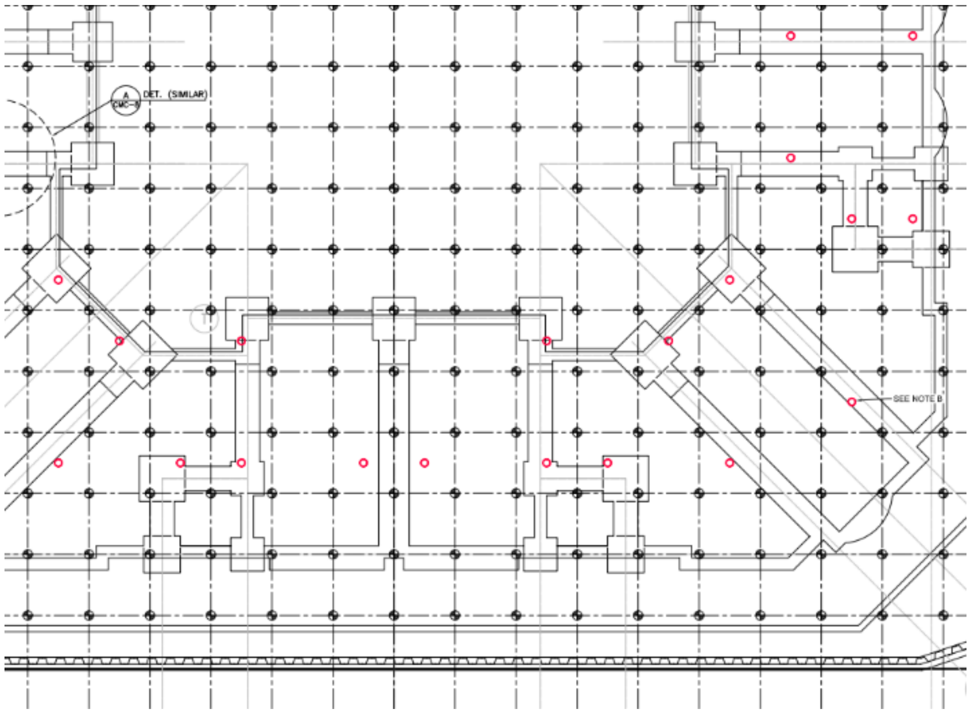
As we, as an industry, became more comfortable with RIs we began using them for more targeted support (see Fig 1b). We recognized that the RIs, as designed, were underutilized and began designing them more more strategically and with higher allowable stresses (e.g. 7 MPa (1000psi). Owners and developers saw an opportunity to reduce costs further if we could load RIs to higher stresses and use fewer elements. The opportunity to reduce costs on the structure itself was also recognized. By designing footings to larger bearing pressures (it is not uncommon to see RIs used on projects with required bearing capacities of 8 to 10 ksf), spread footings can be made smaller, thereby saving time and money. RIs became more commonly used on sites where the soils were poor all the way to the ground surface, so that the RIs were providing bearing capacity and mitigating settlement. With high applied loads and poor soil conditions, the behavior of the RIs becomes more ambiguous, and design considerations need to be more rigorous.

Similarly, owners and contractors see potential savings in the LTPs, frequently requesting the approval of alternate materials and thinner platforms. While sometimes those requests have led to the use of more sustainable materials, such as recycled concrete aggregate (RCA), they have often led to more rigid support of the system with less redundancy, especially in cases where thin or no LTPs are used under rigid concrete elements (e.g. footings or mats).

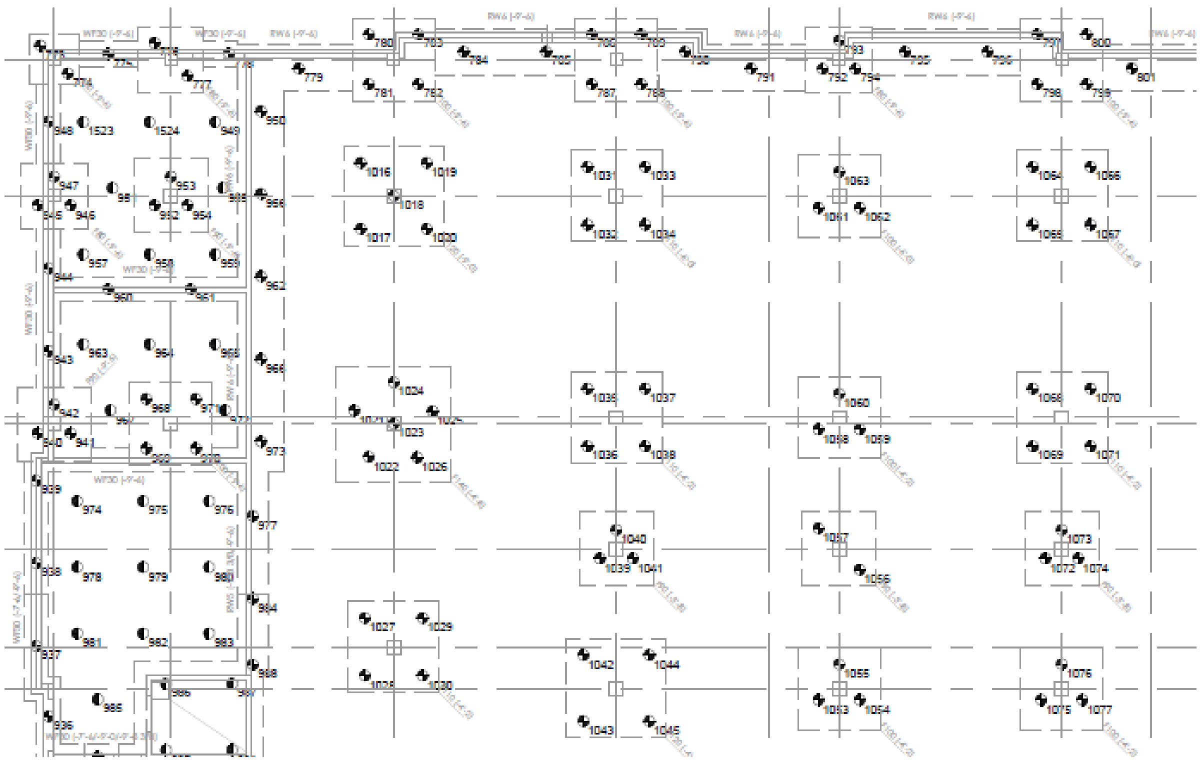
Through this evolution, we have traveled the spectrum of applicability of RIs. Figure 2 shows a spectrum of applicability for RIs including the key factors used to locate individual project conditions on the spectrum. RIs can, have, and should be used at any point along the spectrum, provided that all parties acknowledge their place on the spectrum and consider its impacts and understand the design.

With that, comes the need for reasonable and realistic project criteria that is optimized and is not overly conservative. RIs are generally designed to performance-based criteria; namely, allowable total and differential settlement and a required allowable bearing capacity for supported foundations.

Shallow foundations are typically designed to 1 inch of long-term settlement, as this settlement is acceptable for most common construction. RIs provide economical solutions that will limit long term settlement to 1 inch when the site is not suitable for shallow foundations. For most typical structures, the use of piles, which result in virtually zero settlement, is not warranted.



(a)



(b)

Figure 1. (a) Example of RIs placed in a grid across the site without placing elements directly beneath the strip and spread footings (b) Example of targeted support using RIs (RIs are placed directly beneath the loaded areas and foundations)

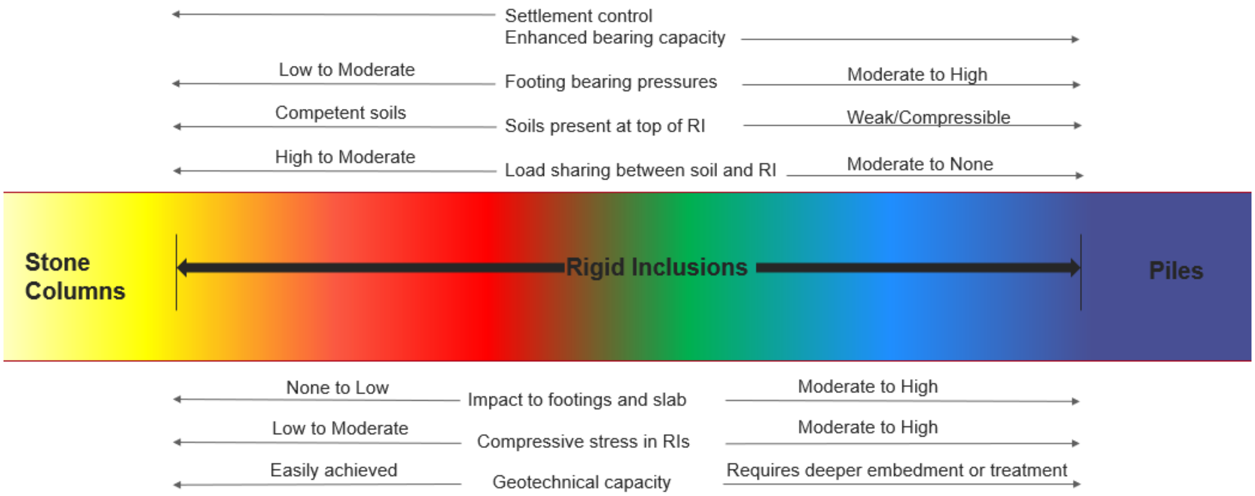


Figure 2. The Rigid Inclusion Spectrum

HISTORY OF RIGID INCLUSION USE

While it was never intended for RIs to replace piles, there are many similarities between the two systems, so the lines between RIs and piles are easy to blur. While piles have been used for centuries under the simplifying assumption that they carry 100% of the structure loads deep into the ground, in fact, RIs are just an advancement on piling design that more fully analyzes and appreciates the soil structure interaction that takes place for a group of elements and does not discount the contribution of the soils to the overall system. The other primary difference is that the structural design stops at the shallow foundations (mats, spread footings, strip footings, slabs) while piling designs fully attach to these elements, in support of the assumption that 100% of the load is in the piles. In its introduction, the ASIRI reference document likens RIs to pile raft foundations, indicating that the theory behind the design and performance of RIs and pile raft foundations is the same but that RIs are typically separated from the structure by an LTP (ASIRI, 2012).

The following four examples show RIs use long before their acknowledgement as RIs. The creative use of “piles” in these examples drew on the same principles and assumption of behavior that are the basis of current RI design.

Example 1. In the mid 1800’s, in Boston’s Back Bay fill was placed over the salt marsh organic deposits overlying the desiccated crust of the Marine Clay, known as the Boston Blue Clay. This granular fill was placed to get above the ground water table and support the westward expansion of the city from the harbor. The typical three- or four-story masonry and wood townhouses were placed on stone block foundations. The stone blocks were stacked on wood cribs that sat on untreated wood piles. The wood piles were driven through the granular fill and organics to be founded in the desiccated clay crust. Today, many of these historic structures have experienced some settlement due to the deterioration of the wood in the tidal zone, losing direct contact with the cribbing; however, there is still substantial settlement control, since the remaining part of these piles is “bridging the organics” through dragdown from the fill, and preservation of the resistance established in the clay. These piles are now, by default, acting as rigid inclusions. In cases where the wood mats were placed at lower grades directly in the organics, the deteriorated piles below resulted in more settlement, and underpinning restorations have been required (personal conversations between the authors and Michael Walker of GEI Consultants, Inc. and various principals at Haley and Aldrich).

Example 2. The Rion-Antirion Bridge, completed in 2004, crossing the straits in Athens, Greece consists of four large main towers that support cable-stayed spans in an area of very high seismicity. Initial studies indicated that deep piles were needed under these towers. The seismic forces induced due to the strong rocking of the towers in a seismic event made the pile design and construction impractical. A novel concept based on the thinking of rigid inclusions by senior executives in the authors' company was proposed to stiffen the response of the towers on the sea floor without rigid connections. A group of large steel pipe piles covered with a one-meter-thick "load transfer platform" was used in lieu of direct connection. The steel pipe piles were referred to as inclusions to respect the fact that they would not behave exactly as would traditional piles.

This stiffening of the soils under each tower provided the appropriate settlement control and seismic response under the structure and allowed the ground to participate in the support, while the LTP acted as a seismic damper, tempering the base demand. The constructability and economy was greatly enhanced with this advanced and novel thinking (Pecker, 2006).

Example 3. The Mandalay Bay Hotel underpinning. In the summer of 1998, the author (Pearlman) was called in to an emergency project in Las Vegas, Nevada where a 42-story concrete tower core resting on a 7-foot-thick (2.1 m) concrete mat was settling at the rate of 13 mm (½ inch) per week. This mat was designed for 335 kPa (7 ksf), as was typical at the time, but the underlying natural caliche "lower mat" was excavated to attain a certain site grade, so instead this mat was lying on clay. Deeper borings taken on an emergency basis while designing the fix were taken to 107 m (350 feet) with no hard bottom found, just many deep layers of clay with sand lenses (described as a deep alluvial wash). The proposed solution was to install 536 fully-grouted (externally and internally) micropiles to a depth of 61 m (200 feet). The piles were also attached to the mat and load was jacked into each one of them. Several piles were instrumented (Pearlman, 2000, Richards and Kartofilis, 2006). The instrumentation showed that, in fact, the stresses in the piles continued to transfer down as they found equilibrium with the surrounding soils. Small but tolerable settlements continued after the project was completed and the building was opened. While the micropiles were thought of as piles at the time, they work as a big group of friction piles in a very deep half-space. They are, by definition, rigid inclusions, since the soil is also in play and participating in maintaining the settlement control and life safety of this large structure.

Example 4. In 2009, Mr. Clyde Baker, PE, Hon M.ASCE, gave a Terzaghi lecture to the ASCE Geo-Institute on the topic of "settlement reduction piles" (Baker, 2009). He discusses large building construction on sites in Chicago where mats are routinely placed on over-consolidated clay, but in some cases he wanted to further reduce settlements using piles with non-traditional design. He allowed these settlement reduction piles to carry higher stresses and find their equilibrium together with the soils, resulting in less settlement. These piles are, by definition, rigid inclusions. It worthy of a note and great thanks to the late Clyde Baker, that when the emergency solution for the Mandalay Bay was proposed to the owner's team, some of the consultants were highly skeptical, and it was Clyde that said, "This will work".

RIGID INCLUSION APPLICATIONS

While often blurred, the distinctions between piles and RIs shown in Table 1 are recognized in industry.

Table 1. Main distinctions between piles and RIs

Piles	Rigid Inclusions
Structurally connected to the structure through use of a pile cap or structural slab	Often separated from the superstructure through use of a load transfer platform (LTP)
Reinforced full-depth to resist axial and flexural forces	Generally unreinforced to resist axial compression only (reinforcement may be provided if tension or flexural forces are present)
Designed to take 100% of the applied load and ignore the strength of the soil	Designed to share load with the soil – generally RIs resist less than 100% of the applied load
Expected settlement is minimal – generally less than ½”	Design is optimized to meet settlement criteria, which is generally 1 – 2 inches depending on the structure.
Embedded in very dense soils or bedrock	Embedded in medium-dense to dense soils

In current practice, RIs are used on a wide variety of sites and for support of small commercial structures, storage tanks, large warehouses, parking garages, embankments, walls, and more. RIs can be installed through most natural soils, high water content peat and organics, and municipal solid waste (MSW). Therefore, the range in projects that can benefit from the use of RIs is vast. Figure 2 shows a spectrum of applicability for RIs including the key factors used to locate individual project conditions on the spectrum.

Project conditions that fall on the left end of the spectrum more closely resemble and will behave like traditional ground improvement. Similar to when stone columns are used, only small improvement is required to the initial conditions to meet the project requirements. Project conditions that fall on the right end of the spectrum more closely resemble piles and will behave similar to deep foundations. Projects that fall on the left end of the spectrum can likely be greatly optimized using ground improvement and large savings in time, money, or both are enjoyed. Likewise, projects on the right end of the spectrum may not benefit as much from optimization due to the large demands on the system, but RIs may still appropriately meet the performance criteria.

SETTLEMENT MITIGATION VS BEARING CAPACITY IMPROVEMENT

There is a clear bifurcation in thinking when sufficient bearing capacity exists; therefore, no life safety issue is present. In this case, ground improvement is required purely for serviceability. Many techniques are applicable and they are typically selected for overall economic value (constructability, value, schedule, etc). Where the unimproved soils do not provide sufficient bearing capacity, the choices become fewer (e.g.. piles, drilled shafts, RIs, or soil mixing). The risk also increases – the consequence of failure of the RIs could lead to a life-safety condition. On the far left of the spectrum, the factor of safety for bearing capacity of the footing is generally 3.0. As you move to the right on the spectrum the minimum factor of safety for bearing capacity of the footing should be linearly interpolated between 3.0 and 2.0 as a function of load sharing between the soil and the RIs.

Examples of sites where RIs are used for settlement control are ones with thick layers of competent soil (such as granular fill or stiff clay) at the ground surface underlain by soft soils such as soft clay, organics, peat, and other compressible soils. The unimproved settlement in the soft soil can be significant and these layers can only be bridged with something that does not rely on the surrounding soil to provide confinement. Once the soft layers are bridged, a serviceable foundation system is created, and a conventional facility may be constructed. At these sites, the granular fill becomes part of the ground improvement system. Not only does it provide bearing capacity for the foundations, but it also facilitates load transfer to the RIs. Generally, this fill allows for the use of wider RI spacings because the load transfer is not limited to the thickness of the LTP above the RI tops. Figure 3 (left) shows Soil Profile 1, a typical soil profile that would fall into this category. A 5 meter (15 foot) thick layer of granular fill allows for the design to be optimized while mitigating settlement from the organic silt and peat below. However, the magnitude of the unimproved settlement is also a key factor in the amount of optimization possible and must be considered in how the RI is designed and tested. As the magnitude of the unimproved settlement increases, the placement of the project on the RI spectrum shifts to the right.

Since not all sites have a competent layer of soil near the ground surface or at the foundation bearing elevation, sometimes the load transfer must happen entirely within the LTP. The soil at the ground surface is too soft to transfer load to the RIs without causing unacceptable deformation. To allow this load transfer to occur, the RI spacing can be tightened or the LTP can be stiffened, either by thickening it or by treating it with lime, cement or other additives. Often, a cementitious LTP, commonly referred to as a mudmat, is used beneath footings that are at or near the top of soft, compressible layers or near the water table. This cementitious LTP not only eliminates concerns with bearing capacity of the system, since the load is transferred directly into the RIs, it also greatly improves constructability of the LTP and the footing. Often, cementitious LTPs are required because adequate compaction of a granular LTP cannot be achieved over such soft or wet soil conditions. (Geogrid is not typically used to stiffen LTPs under buildings because the amount of deformation required to mobilize the strength of the geogrid is too large before it can be effective.)

Figure 3 (right) shows Soil Profile 2 with soft soils near the ground surface. While granular fill exists at the ground surface, it is less than 2m (~7 feet) thick, leaving the bottom of footing elevation to be just above (or in) the organics. The organics will not provide a sufficient factor of safety against a bearing capacity failure of the footing, so the RIs will be required for life-safety, as shown in Tables 1 and 2.

Figure 4 shows the approximate location of each soil profile on the RI spectrum. Note that what is shown is a starting point based on the soils and the need for the RIs to contribute to bearing capacity. As additional project information becomes available, projects may move to the right.

To illustrate the importance the soil plays in the design of RIs, let's use these two soil profiles and evaluate the design of RIs under a 3-m-square (10 foot) footing loaded to 190 kPa (4 ksf) supported by 40-cm-diameter (15.6-inch) RIs. The settlement criteria is 25mm (1 inch) and the bottom of footing elevation is 1.2 m (4 ft) below existing grade with no changes in site grades. We evaluated the settlement of the RIs using Menard's proprietary design methodology and estimated both unimproved (footing only) and improved (footing and RIs) bearing capacity using traditional bearing capacity equations (Das, 1999).

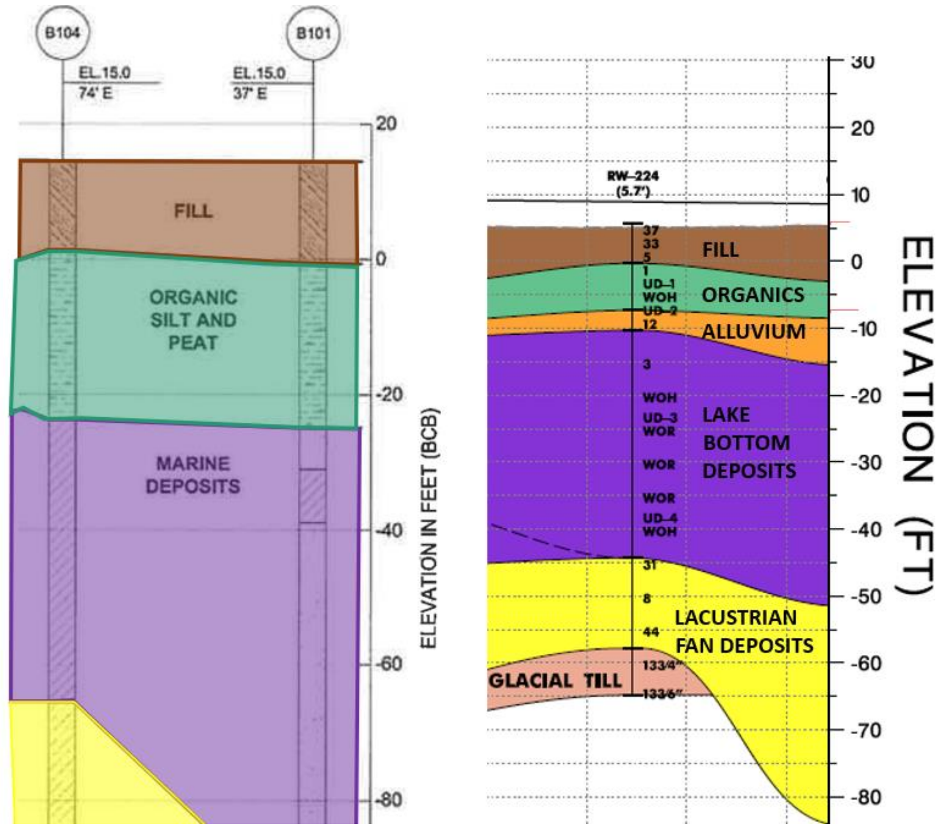


Figure 3. Soil Profile 1 (left) – competent soils near the ground surface and Soil Profile 2 (right) - soft soils near the ground surface

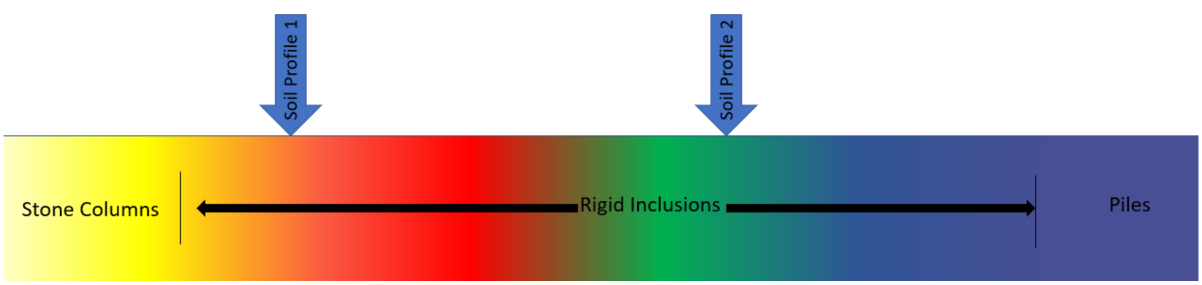


Figure 4. Approximate location of Soil Profiles shown in Figure 3 on the RI Spectrum

As shown in Table 2, the design for Soil Profile 1 has fewer RIs and lower embedment in the bearing layer. The load sharing observed indicates that the soil is supporting a large portion of the applied loads; therefore, the RI design is well-optimized. For soil profile 2, a more robust design is needed to achieve 25 mm (1 inch) of settlement and provide the required 190 kPa (4 ksf) bearing capacity.

So, while RIs can be used on sites with soft soils at the ground surface, the design for the same project will be better optimized (wider spacing, lighter RI loads, smaller elements) on a site with a competent soil layer at the ground surface than one without. When RIs are used on sites with soil profiles similar to soil profile 2, the design, analysis, and considerations for the RIs are more complex and may require more detailed interaction with the structural engineer and contractor (i.e., the footing and slab design may need to consider the impact of the RIs, the RIs are heavily loaded because load sharing with the soil is low, and the system may not be redundant).

Table 2. Results for a 3-m x 3 m (10-foot x 10-foot) footing loaded to 190 kPa (4 ksf)

	Soil Profile 1	Soil Profile 2
Unimproved Settlement	38 mm (1.5 inches)	150 mm (6.0 inches)
Improved Settlement	20 mm (0.8 inch)	20 mm (0.8 inch)
FS against bearing capacity failure of footing on unimproved soil	3.7	1.1
Purpose of RI	Settlement Mitigation	Bearing Capacity and Settlement Mitigation
Area Replacement Ratio	2.6%	5%
Embedment in bearing layer (ft)	1 m (3 ft)	1 m (3 ft)
Max load per RI	410 kN (93 k)	396 kN (90 k)
Load sharing (soil load to RI load)	54% to 46%	10% to 90%
FS against bearing capacity failure of footing and RIs	4.8	2.7

IMPACT OF LOADING CONDITIONS

Another key factor that impacts the design and behavior of RIs is the magnitude of the load we are requiring the RIs to support. Focusing on footings specifically, the required bearing pressure is commonly 6 ksf and above. As those bearing pressures increase further, the design of the RIs needs to consider not only the applied loads but also the geometry of the footing. Enough RIs are required to adequately support the loads, but minimum clearances from other RIs (3D to 4D) and the edges of the footings (varies based on contractor tolerance) need to be respected. The result can be the use of fewer, larger, more heavily loaded RIs as opposed to using more, smaller lightly loaded RIs, which can reduce redundancy and increases the loads in each RI. It also results in stress concentrations on the footings that may require changes to the footing design, or a re-arrangement of the column patterns. Footings should be designed assuming that it is being uniformly supported by the soil, and when critical, checks should be made on the footings for the actual pressure distribution (i.e. soil pressure share and the calculated concentrated load at the top of each RI). With intelligently oriented patterns, the moments and shears in the footing can be respected, but checks are required verify this. These footing checks can be performed by the structural engineer of record or the specialty contractor, provided there is transparency and shared information among the parties. Regardless of the loading, it is critical that the project team understands the behavior of the system and coordinates as necessary.

Using soil profiles 1 and 2 and the footing example evaluated previously, Table 3 compares the results from Table 2 to the results when the bearing pressure on the footing increases from 190 kPa to 380 kPa (4 ksf to 8 ksf). The results further support the notion that soil profile 1 will require a leaner design than soil profile 2. It also shows that as the bearing pressure increases, more of the load is supported by the RIs than the soil.

Table 3. Results for a 10-ft x 10-foot footing loaded to 190 kPa (4 ksf) and 380 kPa (8 ksf)

	Soil Profile 1		Soil Profile 2	
Bearing Pressure	190 kPa	380 kPa	190 kPa	380 kPa
Unimproved Settlement	38mm (1.5in)	54mm (2.5 in)	160mm (6.2in)	300mm (12in)
Improved Settlement	20mm (0.8in)	25mm (1.0in)	20mm (0.8in)	25mm (1.0in)
FS against bearing capacity failure of footing on unimproved soil	3.7	1.8	1.1	0.6
Purpose of RI	Settlement Mitigation	Settlement Mitigation & Bearing Capacity	Settlement Mitigation & Bearing Capacity	Settlement Mitigation & Bearing Capacity
Area Replacement Ratio	2.6%	7.8%	5%	10.5%
Embedment in bearing layer	0.9m (3ft)	1.5m (5ft)	0.9m (3ft)	1.7m (5.5ft)
Max load per RI	400 kN (93k)	490 kN (110k)	396 kN (90 k)	440kN (99k)
Load sharing (soil to RI)	54% to 46%	18% to 82%	10% to 90%	1% to 99%
FS against bearing capacity failure of footing and RIs	4.8	3.0	3.0	2.2

As shown in Table 3, soil profile 1 provides an adequate factor of safety against a bearing capacity failure at a pressure of 190 kPa (4 ksf); however, when the pressure is increased to 380 kPa (8 ksf), the RIs are required to meet the minimum factor of safety against a bearing capacity failure. Similarly, for soil profile B, an adequate factor of safety is achieved since 99% of the load is resisted by the RIs at the top. In that case, bearing capacity is controlled by the geotechnical capacity of the RI, not the bearing capacity of the soil.

Consideration should be given to the need for such high bearing pressures and RI loads as these factors remove redundancy from the design and are more likely to require the RIs to provide bearing capacity. While redundancy is not always necessary, it provides an additional layer of flexibility to the design. More lightly-loaded RIs can be shorter, thereby reducing installation time. It also allows for the RI to support unexpected changes to the design of the structure or field conditions without modification or enhancement.

CONCLUSIONS

The use of RIs is beneficial to a wide spectrum of projects, though the magnitude of the observed benefits varies depending on the specific details surrounding the project. For sites falling at the left end of the spectrum, the benefit is significant and should be respected. The purpose of the RIs and the risk tolerance of the project team should be discussed and understood by all the constituents. For sites at the right end of the spectrum, many of the considerations and requirements that apply to piles apply to RIs. However, the use of RIs for a similar purpose as piles may still result in overall savings in cost, time, and materials and will meet the project criteria. Economics, schedule, and ease of construction can all drive the decision, provided that the RI designer has the appropriate experience and design rigor to evaluate the system thoroughly and responsibly.

The appropriate use of RIs requires creative thinking and an in-depth consideration of how the system will perform in both short- and long-term conditions. Often, strict adherence to traditional rules, simplifying assumptions and gross application of extreme cases obscures the purpose and true requirements of the foundation system. The industry is comfortable with the behavior of deep foundations, specifically piles, and has developed guidelines and codes to aid in their design, installation, and testing. The methods the industry uses for the evaluation of deep foundations is based on a long history, and has inherent conservatism applied to it at different levels: from the performance criteria provided to the parameters and properties used to evaluate the soil and material conditions and the design of the foundations themselves. In turn, that often results in a more robust system than is needed. Instead of focusing on the process and procedure to determine the foundation design, the use of ground improvement, specifically RIs, requires consideration of the purpose of the foundation and the implications of a more economical but well-designed system. Pile codes are an historical snapshot of practices in effect at the time they were written. RIs are "the piles of the future" and we in the geotechnical community need to embrace this improvement completely with intelligent engineering based on solid principles. With that spirit, we will collectively move forward in improving our service to the profession and our clients.

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