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Geophysical and *in situ* testing applied to site characterisation for non-engineered structures in developing regions

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ABSTRACT: Residential dwellings have been estimated to represent more than three quarters of the building stock around the globe, most of which are not believed to have been properly engineered (that is, designed by architects or engineers and constructed by skilful workers with adequate materials). Narrowing the scope to developing countries, over a 90 percent of the population is deemed to be living, working or studying in non-engineered buildings. In earthquake-prone regions, these weak structures can become deathtraps for their occupants, forlornly adding to the casualty lists of recent and past seismic events. Thus, improving seismic resilience for vernacular housing has increasingly become a main theme for researchers. Also, other geotechnical issues, such as subsidences, slope instabilities, excessive settlement on soft soils, groundwater, inadequate designs, etc., are responsible for substantial risk of structural damages, ranging from small structural pathologies to major disasters. One of the keys to develop new safe and efficient foundation designs, or to retrofit existing ones, is to make available portable and low-budget ground probing techniques. This document will describe some of the most feasible *in situ* devices available, as well as discuss how seismic and electric methods can be used as portable and powerful tools to characterise both the strength and the stiffness of soils thanks to recent developments in stablishing the relationship between geophysical results and traditional geotechnical parameters (such as the SPT, the angle of internal friction, shear strength, etc.), with the help of statistical methods and dimensional analysis techniques.

1 INTRODUCTION

1.1 *The role of engineering in a sustainable development frame*

Among the seventeen Sustainable Development Goals declared by the United Nations (UN General Assembly, 2015), some key targets should benefit from the combined effort of engineers and researchers in the field of ground engineering in the least developed and developing countries, especially:

- Providing technical education (targets 4.c and 9.5) through the contribution of qualified trainers and researchers
- Developing resilient infrastructures (target 9.1), building stock (target 11.1) and historical sites (11.4), while promoting the use of local resources (target 11.c)
- Protection of population and the physical environment against catastrophic phenomena (target 11.5), implementing integrated risk management policies

Thus, two main themes should walk hand in hand in order to attain those goals:

- Education: specific technical and psycho-environmental training should be provided not only for those engineers living in the developing regions, but also for those coming from more developed countries, as they are seldom given the specific training to solve the complex earth system problems involved in those regions (Amadei, 2004; Francisca, 2011). Experiences such as those related by Fukubayashi and Kimura (2014) or by Sandekian et al. (2014), emphasise the prominence of good communication with local communities as a key for success in implementing new engineering techniques
- Development of sustainable novel solutions to new or preexisting problems

1.2 *Population growth and non-engineered building stock*

While there has been a reduction in the population living in slums in most regions of the world in the last 15 years (Way, 2015), thus achieving a meaningful life quality improvement for millions of people, there is still a long road ahead: as far as almost a 30 percent of the urban population in developing countries (as in 2014) still dwells in slums. Although that percentage was much higher twenty five years ago, the number or people living in those slums is increasing in absolute numbers due to population growth, as described in table 1:

Table 1. Slum residents in urban areas (Way, 2015)

Year	Absolute number of residents (Millions)	Percentage of total urban population
1990	689	46.2
2000	830	39.4
2014	881	29.7

If we combine the slum building stock with the vernacular housing in rural areas, according to Oliver (2007), nine out of ten buildings around the world are estimated to be non-engineered structures, accommodating over a 90 percent of the population in developing or underdeveloped countries (Arya, 2000). Judging from recent population growth projections, and examining the extremes of the growth tendencies, although during the present century Europe will experiment a population decrease, Africa will contribute with over 3.2 billion people to the total world increase (which is projected to grow from 7.3 billion to over 11 billion people), as shown comparatively in figure 1:

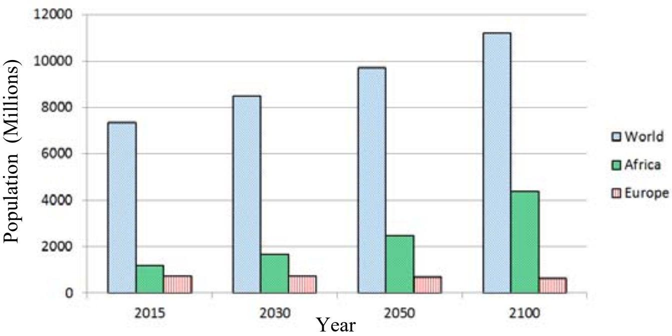

Figure 1. Increase in population between 2015 and 2100 in the world compared to Africa and Europe, adapted from United Nations (2015).

These figures only emphasise the importance of upgrading the building stock in the least developed countries, as the population living or working in non-engineered buildings subject to natural or artificial risks of collapse will grow otherwise in the next decades. In this context, several prominent engineering institutions have already acknowledged the crucial task in our hands, as the recent *"Madrid Declaration (…) for sustainable development and action for the climate"* (SICE, 2016) or the *"ASCE Vision for Civil Engineering in 2025"* (ASCE, 2007). These are paradigms that stress the necessary active role of the engineering global community in the future of developing countries.

1.3 *Geotechnical hazards and risks*

To understand our role in this scenario, we must first fathom the magnitude of the challenge. While sometimes both *hazard* and *risk* have been interchangeably used (Gkoumas, 2008; Renzi, 2009; Wang, 2008), it is important to acknowledge the difference between both terms in engineering: a hazard must be seen as an event that may originate a potential harm over a natural or artificial system, while a risk measures the probability of that hazardous event to have a negative consequence on such system. For instance, while the hazard of an earthquake in a sector of a city in which slums coexist with adjacent high-rise districts may be the same, the risk of structural damages and life losses is greater in the poorer, non-engineered part of that urban settlement.
Thus, the task of geotechnical engineers should be that of risk assessment and management of foundation design and ground structure interaction. On that regard, ground characterisation should be among the most important tools.

1.4 *Lost lessons after infrequent hazardous phenomena*

In many developing countries, catastrophic infrequent events (such as earthquakes, landslides, etc.) do not permeate into the traditional building traditions (McWilliams and Griffin, 2013), as opposed to those countries used to frequent low-magnitude events. As a consequence, the lessons that should have been acquired by the community are washed out soon after the event.

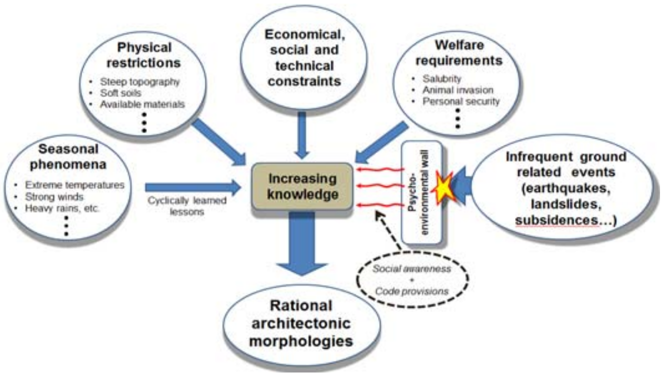

Figure 2. The mechanisms behind building morphologies, adapted from Ortiz-Palacio et al. (2015)

While other factor slowly help to shape vernacular housing architecture, infrequent but catastrophic events collide with psycho-environmental walls, which are built by lack of awareness, institutional indifference, superstition, etc. In figure 2 it is represented how building morphologies are reshaped by the environment.
For example, during the 20th century, around a 75% of deaths during or in the aftermath of earthquakes are believed to have been caused by the collapse of non-engineered masonry buildings (Mallick, 2015), which would mean that those structures claimed over 1.3 million casualties, according to the seismic-related total death toll described by Chowdhury and

Flentje (2007). Ground characterisation should be a stepping stone on which to support the means to demolish that psycho-environmental wall.

2 GROUND CHARACTERISATION IN DEVELOPING REGIONS

Financial access and technical restraints are two of the main obstacles pointed out by many experienced practitioners to undertake a proper ground characterisation for foundation design in developing communities. In the budgetary respect, paradoxically, a good prior characterisation of the soil conditions should always mean a lesser range of variability of the budgetary uncertainty involved in any project. For instance, MacDonald (1994) compiled some UK Highway Projects budget deviations due to geotechnical issues. In the report, the uncertainty in geotechnically related problems is proved to increase as the ground investigation cost/construction tender cost ratio decreases: when the ground investigation represented less than 1% of the construction tender cost, increases could reach in some cases almost a 100%, while ground investigation over a 5% reduced maximum increases down to a 15% (Whyte, 1995). Therefore, probing techniques should always be considered as an investment. Adapting to geotechnical site characterisation the effort curve described by MacLeamy (2004), in figure 3 we can compare the traditional building process against the ideal project scheme that should be adopted, in tune with new Building Information Modelling approaches to traditional engineering problems (Morin et al., 2014):

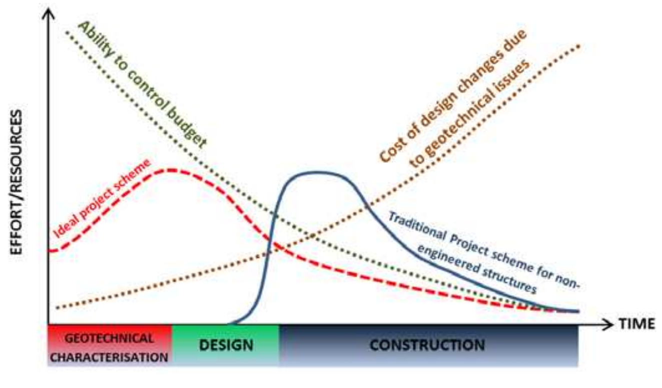

Figure 3. Effort curves in non-engineered buildings projects, adapted from MacLeamy (2004)

Once the construction has started, any geotechnical issue will consume far more resources if ground characterisation has not been properly performed. The problem is how to implement the site characterisation phase in complex environments. Nowadays, a wide range of *in situ* tests are available (Monnet, 2015), and as practitioners around the globe share their results in the engineering community, the interpretation of these results gives wider possibilities every day. However, these techniques are not widely available in developing countries, which render their use as very restricted in many occasions. Availability of specialised devices and trained personnel to use them is critical to define the potential use of these techniques (Robertson, 1986). Many experiences on these matter have been described (e.g.: the difficulty of finding a pressuremeter device in Pakistan summarized by Rehman (2010), or the unavailability of operative *in situ* and lab equipment described by Orsmond (2007) in Jamaica).

3 IN SITU TESTING: SOME FEASIBLE TECHNIQUES

As drilling rigs are not always available to perform boreholes in which not only samples of the soil are retrieved, but also where a wide variety of other of mechanical tests can be carried out –such as the Standard Penetration Test or the Pressuremeter Test, to name two of the most common ones-, during the last decades many researchers have been developing new portable low-budget devices, such as:

- *Dynamic Cone Penetrometers (DCP)*: this type of light testing devices were first designed in a primitive fashion at the end of the 17th century (Burnham and Johnson, 1993), but the first *modern* implementation was made by Scala (1956). Soon, many researchers started developing correlations between this technique and several other tests (CBR in pavements, unconfined compressive strength, shear strength, etc.) until our days (Jones and Harvey, 2005; Luo et al., 1998; Scala, 1956). While it can be easily transported and is relatively inexpensive, it requires a lot of physical resistance and its manual-operation nature introduces uncertainty in the results as penetration energy can vary from one blow to another. Also, this method has analogous limitations for use in cohesive soils as other dynamic penetration equipment.
- *Swedish Weight Sounding (SWS):* this light penetration equipment was developed by the Geotechnical Committee of the State Railways of Sweden as a multipurpose, low-cost *in situ* testing device (Habibi et al., 2007). It consists of a screw-pointed rod, manually driven to different depths under several static weights (Orense et al., 2014). During the test, the static penetration under such weights and the necessary torque after the static phase to further penetrate into the soil 25 cm is then measured. These parameters are then converted into SPT or CPT equivalent results. Although this equipment can perform low-cost and rapid tests (including approximate liquefaction assessment), there are some significant disadvantages, as the deviations in soil characterisation

due to rod friction or the low resolution for soft soils (Orense et al., 2014; Tanaka et al., 2012)
- *Screw Driving Sounding (SDS)*: recently devised in Japan (Orense et al., 2014), this enhanced version of the SWS overcomes some of its previously mentioned disadvantages, automatizing the test (thus, minimising the influence of operator deviations) and implementing rod friction measure systems
- Other devices: some good comprehensive list of other light and portable equipment, as the Airfield Cone Penetrometer, the Trafficability Cone Penetrometer, the Rapid Compaction Control Device, etc., can be found in Kianirad (2011). Some other recently developed equipments, such as the Rapid Soil Characterisation System (RapSochs), are being extensively reported, quickly widening their feasibility for ground characterisation (Gamache et al., 2009; Kianirad et al., 2011).

Many of these techniques incorporate man-portable, low-cost devices which allow us to classify them as potentially useful tools for geotechnical site characterisation in developing regions. However, as most of the time they could be used as stand-alone tests, efforts on expanding the available data and correlations should be carried out by the experts, in order to increase their possibilities.

4 GEOPHYSICS: EXPANDING POSSIBILITIES

The potential of geophysical techniques is growing each year, as testing devices are being continuously enhanced, decreasing in volume and weight while their versatility and possibilities are increasing. In parallel, the interpretation algorithms and the software that implements those are improving the resolution of these tests, even amplifying their possibilities.

The pieces of equipment can be easily carried as baggage by a reduced team of researchers to any place in the world, as the authors have verified on many occasions: just three people are enough to easily carry to different countries one seismograph, one resistivity meter, 24 geophones, 36 electrodes, and over 300 m of cables, along with auxiliary devices (laptops, batteries, etc.) in just four checked pieces of luggage and three cabin bags. The authors have successfully transported equipment in this fashion to Mexico, Bolivia, Nigeria, Jamaica, Uruguay, Costa Rica, etc. without ever encountering any problem.

Although this kind of systems are not usually inexpensive, through the collaboration of governmental institutions, non-profit organisations and researchers, these techniques can travel to places where other probing machinery has been proved to be unaffordable or unable to be transported, and their use can mean a significant difference to enhance the design process for traditionally non-engineered housing environments, as was shown in figure 3.

4.1 *Seismic methods*

Seismic surveys are known to offer many possibilities through the direct analysis of their resulting data: strata disposition (Milsom and Eriksen, 2011), detection of water or gas (Begay et al., 2000; Dai et al., 2004; Grelle et al., 2013), definition of subsoil cavities (Grandjean and Leparoux, 2004; Sheehan et al., 2005), landslide risk assessment (Hagedorn, 2014), etc.

Seismic refraction and surface wave tests are increasingly becoming very popular both as stand-alone field tests or as combined tools using several strategies: as pseudo joint P-wave refraction and surface wave 2-D inversion analysis (Ivanov et al., 2000), combined SH-wave refraction an MASW explorations (Yordkayhun et al., 2014), joint MASW and ReMi methods (Yordkayhun et al., 2014) or integrated study of Rayleigh-wave and Love-wave surveys (Dal Moro, 2014), to name only few.

One of the additional potential uses of seismic techniques in developing communities is to relate seismic results (namely, wave propagation velocities) with other geotechnical parameters traditionally used in foundation design, slope stability estimations, etc. Recent tendencies have tried to establish the relationship between the SPT-N blow count in Standard Penetration Tests with the s-wave propagation velocities, with good determination coefficients (see Thaker and Rao (2011) for a complete compilation of such correlations). However, s-wave analysis through surface waves recording can be quite difficult sometimes, and it can lead to inaccurate estimations of those velocities (Dal Moro et al., 2015). On the other hand, usually p-wave profiles can be more adjusted to the real underground properties of a site, if no hidden stiff layers are close to the surface.

With this idea in mind, the authors have crossed p-wave propagation data with SPT continuous profiling in several alluvial deposits in Mexico, discovering that while direct SPT-N vs. p-wave velocity present low determination coefficients, under the light of dimensional analysis (Butterfield, 1999), this approach renders good regression results. After the introduction in the dimensional analysis of other parameters such as the effective overburden stress, the unit weight, the void ratio or the saturation degree of the soil –consistent with the geotechnical dependencies described by Foti (2012)-, the determination coefficient increases over 0.9. As many methods used to estimate bearing capacity of foundations, settlement potential, etc., are formulated over SPT-N dependant expressions, this kind of dimensional analysis approaches could be quite useful in the near future to fill the void in previously non-engineered construction initiatives to estimate foundation design parameters.

4.2 *Electric tomography*

Some recent efforts in creating regression models relating electrical resistivity with soil properties such as water content, unit weight, cohesion, angle of internal friction, etc. (Akinlabi and Adeyemi, 2014; Cosenza et al., 2006; Siddiqui and Osman, 2013), have produced wide dispersions, quantified by low determination coefficients. Other approaches (Akinlabi and Adeyemi, 2014; Sudha et al., 2009) have however shown good linear correlations between transverse resistance and average SPT-N, that allow us to be confident on the development of its potential as predictive non-intrusive techniques in the future. On this regard, the authors are currently analysing the predictive character of these techniques. For instance, several tests on alluvial strata in Burgos (Spain) have been carried out to correlate DPSH (Deep Probe Super Heavy) penetration resistance in comparison with inverted resistivity, with results that show encouraging predictive possibilities.

Also, ERT is known a powerful tool to assess the potential existence of sinkholes in karstic systems, as those explored by the authors in Jamaica, as illustrated in figure 4:

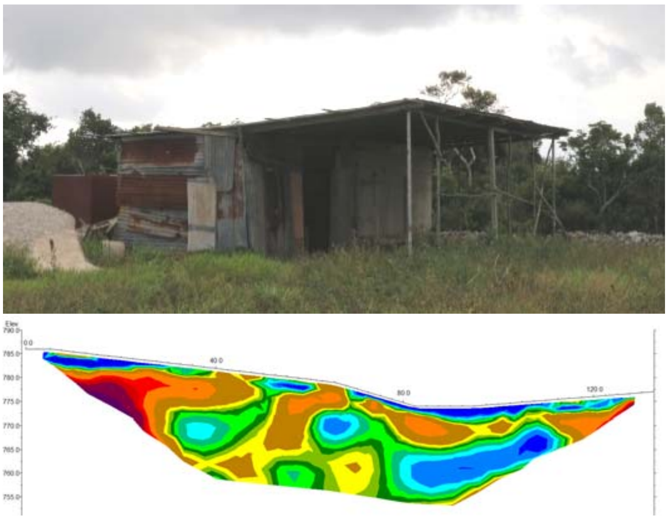

Figure 4. Electric tomography on karstified limestones next to a non-engineer shack in Mandeville (Jamaica)

4.3 *Joint seismic-electric methods*

If geophysical methods as stand-alone techniques have a wide variety of possibilities on the field of site characterisation, recent studies have pointed out the potential behind joint interpretations, using seismic and ERT methods on the same site (Driad-Lebeau et al., 2008; Johnson et al., 2002; Riddle et al., 2010; Sudha et al., 2009).

5 CONCLUSIONS

Devising new geotechnical site characterisation techniques and equipment specifically designed for underdeveloped and developing countries is a responsibility for the ground engineering practitioners and researchers, as the projections of the population living in non-engineered dwellings in hazardous parts of the world along this century is quite alarming. Several possibilities have been described, which outline the lines of research and development that will be required during the next decades.

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