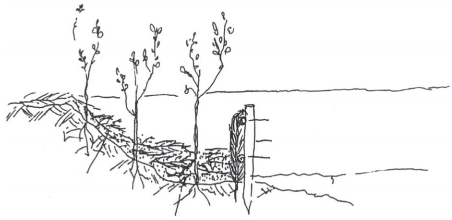

The development of soil bioengineering as an analytical discipline

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Soil bioengineering consists basically of using live material as construction and structural elements in engineering applications related to stabilization of natural systems. The techniques used are not new, however its establishment as a technical and scientific discipline is recent. The current stage of soil bioengineering development is marked by artisan and descriptive approaches. The aim of this work is to propose a program to develop soil bioengineering as a more analytical engineering branch. The historical progress and current stage of soil bioengineering are discussed and related to the historical progress of traditional engineering branches. A program to structure soil bioengineering as a more analytical discipline is suggested in the form of a hierarchical sequence of steps. This structuration contributes to improve the degree of confidence and precision in the professional practice of soil bioengineering applications and also it helps to standardize practice and improving the discipline.

Introduction

Soil bioengineering is a field of civil engineering which basically consists of using plants as engineering material and structural elements.[1] From the very pioneer scientific works on the subject, such as Kruedener's book[2], the technical aspect of this engineering discipline was highlighted. Further its basic technical character, which is similar to other engineering fields of study, soil bioengineering has other basic functions such as ecological, aesthetic and economic finalities.[3] The main interventions of soil bioengineering, regarding its technical function, are: stabilization of slopes, control of erosion processes, ecological restoration and stabilization of the hydraulic condition of open channels. By stressing the focus of soil bioengineering on broader environmental concerns some authors[4] consider that soil bioengineering is a discipline originated in the last century, even though its techniques has been applied for centuries ago in many parts of the world[5]. Apart from this discussion, just recently, soil bioengineering has receiving some scientific treatment as a modern engineer discipline and being subject of specialized bibliography.[6]

The modern engineer concept involves the application of scientific principles to practical purposes.[7] This concept has passed by a gradual development along many centuries.[8] Firstly, engineering work was done by experts whose knowledge was based mainly in experience acquired through years of professional work, empirical observations and even instinctive approach.[9] Nowadays, the engineering practice is most performed using analytical and quantitative design rules. The design rules in many engineering branches tend to course a gradual way from the experience-based (empirical) rules to principles based on a full scientific understanding and explanation of the relevant underlying phenomena.[10]

As a technical-scientific discipline[11], soil bioengineering deals with problems very similar to other civil engineering disciplines[12]. Settled as a distinct engineering field, and not just a new constructive technique, soil bioengineering demands analytical quantitative design guides and codes, standard techniques of experimental engineering science and standard curricula in polytechnic or university courses. Soil bioengineering distinctive characteristic is the use of live vegetative elements as building material.[13] Unlike other technologies in which plants are chiefly an aesthetic component, in soil bioengineering systems, plants are an important structural component.[14]

1 SCHIECHTL, H. M. *Grundlagen der Grünverbauung*. Mitteilungen der forstlichen Bundes-versuchsanstalt Mariabrunn. Wien: Kommissionsverlag der Österreichischen Staatsdruckerei, 1958. 273 p.
SCHIECHTL, H. M. & STERN, R. *Ground Bioengineering Techniques for Slope Protection and Erosion Control*. Wiley, 1996. 176 p.

2 KRUEDENER, A. *Ingenieurbiologie*. Münschen: Reinhardt Verlag, 1951. 172 p.

3 CORNELINI, P. & FERRARI, R. *Manuale di Ingegneria Naturalistica per le Scuole Secondarie*. Regione Lazio, 2008. 226 p.

4 BISCHETTI, G. B. *et al*. On the origin of soil bioengineering, *Landscape Research*, p. 1-13, 2012.

5 GRAY, D. H. & SOTIR, R. B. *Biotechnical and Soil Bioengineering Slope Stabilization*: A Practical Guide for Erosion Control. New York: Wiley, 1996. 400 p.

6 PETRONE, A. & PRETI, F. *Ingeniería naturalística en Centroamérica*. Manuali tecnici per la cooperazione allo sviluppo – Istituto Agronomico per L'Oltremare, Società Editrice Fiorentina, Florencia, 2005. 108 p.

7 RANKINE, W. J. M. *Introductory Lecture on the Harmony of Theory and Practice in Mechanics*: Delivered to the Class of Civil Engineering and Mechanics in the University of Glasgow on Thursday, January, 3, 1856. 22 p.

8 KIRBY, R. S. *et al. Engineering in History*. McGraw-Hill, 1956. 544 p.

9 STRAUB, H. A. *History of Civil Engineering* – an Outline from Ancient to Modern Times. Leonard Hill Limited, 1960. 258 p.
ADDIS, B. *Building*: 3000 years of Design Engineering and Construction, 2007. 640 p.

10 ADDIS, B. *Op. cit.*

The soil bioengineering techniques have been used for many decades, especially in Central European countries. Nowadays, those techniques are being spread over other countries.[15] The main task in these new application regions is to identify plants with a required potential to be used as structural components. The result is that scientifically research has been focused on the characterization of this vegetative material in new biomes. On the other hand minor attention has being paid to quantify the characteristics and plant behavior as engineering materials. According to Morgan & Rickson[16] soil bioengineering is a classic example of a discipline where there is a prominent distance between the practice and the science.

The soil bioengineering current stage, characterized by craft and artisan skills in some of its parts, has been the cause of so many challenges such as restrictions to the use of those techniques by a broader range of engineering applications and professionals. According to Mickovski & Van Beek[17] the lack of more analytical literature, codes of practice and design is a relevant issue on the small interesting and encouragement of engineers to employ soil bioengineering measures. Other possible cause to the marked reluctance to use vegetative methods in preference to conventional civil engineering is, according to Schiechtl & Stern[18], due to the lack of training or lack of personal experience in a relatively new field. However, the very descriptive current stage of soil bioengineering contributes to turn the training process and personal experience gaining a slow and uneven task.

A clear and objective identification of soil bioengineering discipline as an engineering branch can be an important step in order to turn this field more analytical. Since in many ways and situations the soil bioengineering applications are a rediscovery or a reinterpretation of correlated traditional and well-established engineering fields, the very path, gradually performed by those correlated engineering disciplines, can be used to direct, organize and model a similar development on the soil bioengineering field.

This work presents a development program to the soil bioengineering as a technical or engineering discipline. The soil bioengineering concepts and basic definitions are first discussed, followed by a brief presentation of the gradual development of the modern concept of the engineering practice. Next the characterization of soil bioengineering as a distinct engineering discipline is presented. The

[11] PRETI, F. & MILANESE, C. Monitoring ground bioengineering stabilization of landslides in Lazio Region, Italy. p. 231-238, *In*: STOKES, A. *et al*. *Eco- and Ground Bio-Engineering*: The Use of Vegetation to Improve Slope Stability. Springer, 2005.

[12] LEWIS, L. *Soil Bioengineering*: An Alternative for Roadside Management. A Practical Guide, USA Department of Agriculture, 2000. 47 p.

[13] CORNELINI, P. & FERRARI, R. *Op. cit.*

[14] LEWIS, L. *Op. cit.*

[15] DURLO, M. A. & SUTILI, F. J. *Bioengenharia*: Manejo Biotécnico de Cursos de Água. Porto Alegre: EST Edições, 2005. 189 p.
LI, X.; ZHANG, L. & ZHANG, Z. Soil bioengineering and the ecological restoration of riverbanks at the airport town, Shanghai, China. *Ecological Engineering*, 26, p. 304-314, 2006.
PETRONE, A. *Sistema de preparación ante desastres naturales en siete comunidades rurales del Área de Cerro Musún en el municipio de Río Blanco, Matagalpa, Nicaragua*. Cooperación al Desarrollo de Paises Emergentes (COSPE), Fundación Nicaraguense para el Desarrollo Sostenible (FUNDENIC) e colaboración Universidad de Florencia, Nicaragua, 2006. 84 p.
QUINTANA, Y.; PETRONE, A. & PRETI, F. *Capitalización de la experiencia de ingeniería naturalística en Jipijapa, Manabí, Ecuador*. Proyecto reducción de riesgos por desastres en el sur de Manabí, CRIC – Terranueva, V Plan de Acción Dipecho Capitulo Ecuador, ECHO/DIP/BUD/2007/03007, Ecuador. 2009.
ALI, F. Use of vegetation for slope protection: Root mechanical properties of some tropical plants. *International Journal of Physical Sciences*, 5, p. 496-506, 2010.

[16] MORGAN, R. P. C. & RICKSON, R. J. *Slope*

current stage and practices of soil bioengineering are addressed, in correlation to the stages found in the development of the major engineering branches. The main challenges and difficulties of a broader acceptance by professionals of soil bioengineering techniques are discussed, as well, their relations to its current stage. Finally, the program to develop soil bioengineering is presented, discussing in details the steps to achieve a more analytical discipline and pointing out the benefits of such approach.

Development and concepts

On the very first paragraph of his book written in 1958 Schiechtl affirms: "Soil bioengineering is understood as the set of efforts to attain plant recolonization in order to re-stabilize soils". Schiechtl makes clear that this discipline has "as its priority" technical goals by means of using live plants as a tool to obtain soil protection, sediment transportation management, and slope stabilization. However, the ecological, aesthetic, and territory planning soil bioengineering functions are not excluded of its technical primordial finality.

Not infrequently that soil bioengineering techniques has been presented as new-found methods by the specialized literature, however this affirmation relies much more on a rediscovery of a set of knowledge and techniques that are much more ancient than the nowadays called traditional practices. The use of local materials, such as wood and rocks, associated to live plants as construction elements and co-participant in the soil engineering properties improvement process is a simple and even intuitive concept whose origin cannot be determined. Indeed, as evidenced by Gibling & Davies[19], the vegetation naturally has performed a relevant influence on the landscape formation processes, and as consequence, over its present features.

The first collecting, comprising artisan and empirical knowledge, by technical texts specialized in soil bioengineering (even though this term was not yet coined) appeared in the second half of 19th century[20] followed by works mainly correlated to river management, road construction, forestry planning and wood production in the 20th century[21]. In 1941 the engineer Arthur Freiherr von Kruedener coined the german term "Ingenieurbiologie" to designate a new engineering branch or discipline. In the following decades a series of scientific works on the subject were published, with the prominence of the pioneer academic work of the Austrian engineer Hugo Meihard

Stabilization and Erosion Control – a bioengineering approach. London: E & FN Spon, 1995. 306 p.

17 MICKOVSKI, S. B. & Van BEEK, L. P. H. Decision support systems in eco-engineering: the case of the SDSS. p. 231-238, *In*: STOKES, A. *et al. Eco- and Ground Bio-Engineering*: The Use of Vegetation to Improve Slope Stability. Springer, 2007.

18 SCHIECHTL, H. M. & STERN, R. *Ground Bioengineering... Op. cit.*

19 GIBLING, M. R. & DAVIES, N. S. Paleozoic landscapes shaped by plant evolution. *Naturel Geoscience*, 5, p. 99-105, 2012.

20 DU BOYS, P. Le Rhore et Les Riviers a Lit Affonillable. *Annales Des Ponts et Chaussees*, Ser. 5 XVIII, p. 141-195, 1879.
DEMONTZEY, S. *Studien über die Arbeiten der Wiederbewaldung und Berasung der Gebirge*, 1884. 381 p.
SECKENDORFF, A. F. V. *Verbauung der Wildbäche*. Aus Anlass der Reise seiner Excellenz des Herrn k. k. Ackerbauminister Grafen Julius von Falkenhayn nach Südfrankreich, Tirol und Kärnten. 122 Abb., VIII, 1884. 319 p.
SCHINDLER, A. *Die Wildbach-und Flußverbauung nach den Gesetzen der Natur*. 1889.

21 WANG, F. *Grundriß der Wildbachverbauung.* 1902. 706 p.
STINY, J. *Berasung und Bebuschung des Ödlandes im Gebirge*. 1908. 186 p.
KRAEBEL, C. J. Erosion control on Mountain Roads. *USDA* Circular Nº. 380, 1936. 45 p.
STELLWAG-CARION, F. *Eignungsprüfung bei Steckhölzern*. Zentralbl. für die gesamte Forstwirtschaft, Heft 7/8, 1936.
KELLER, E. *Die Bautechnische Anwendung und Durchführung der lebenden Verbauung*. Wasserw. und Technik, Heft½. 1937.

Schiechtl. Even though this early academic work is not analytical in character it is a very important step in the soil bioengineering technical development.

According to Schiechtl[22] the great damages to the European landscape and the difficulties of the post-war period stimulate the use of simple techniques. However, it is evident that the fast industrial and technological development and the yet inceptive environmental concerns, which characterize that period, have decreased the research and practical interest on such techniques.

Nowadays, there is a huge demand, not only technical-related, conducing again the scientific and engineering communities to economic and feasible solutions that make possible or even grant some degree of commitment regarding ecological (environmental) and aesthetic (landscaping) concerns.

Kruedener[23] points out that one of the basic soil bioengineering features is to bridge the natural sciences (mainly botany and ecology) and engineering disciplines. The author speaks in terms of "biology-guided engineering techniques". Approaching the subject on this manner is an essential concept in the soil bioengineering developing.

The original definitions and concepts are, generally, reproduced by the current literature without any remarkable contribution or changing. Pioneers researches such as Kruedener & Becker and Kruedener[24], Schiechtl[25] and Prückner[26] had identified that soil bioengineering has also non-technical characteristics. This is made clear by the constant use of the term "purely technical" interventions when referring to the traditional engineering measures. It is worthy to note that this point of view, regarding the identification of nontechnical soil bioengineering characteristics, shared by these authors, was truly innovative and only in the last years it was truly accepted. According to Kruedener[27] the engineer concerns should not be directed exclusively to the technical design of a given work, but also to its complete adjustment to the environment. He affirms that an engineering work should not be a strange object in relation to the around landscape, but must be completely integrated to it. Those are the principles that always have guided soil bioengineering practice. On the other hand, the pioneer researches were not concerned to develop theirs concepts using a clear distinction between the technical and nontechnical soil bioengineering functions. This has just happened in the last years, when current approaches, such those shared by Cornelini & Sauli and Cornelini & Ferrari[28],

KELLER, E. *Kampf dem Bergschutt*. Deutsche Wasserwirtschaft, Nr. 12. 1938.
KELLER, E. *Lebende Verbauung im Flußbau*. Centralbl. für das gesamte Forstwesen, Heft, 7/8. 1938.
KELLER, E. *Wildbachverbauung und Flußregulierung nach den Gesetzen der Natur*. Deutsche Wasserwirtschaft, Heft 6. 1938.
SEIFERT, A. Naturnäherer Wasserbau. Deutsche Wasserwirtschaft, Nr. 12. 1938.
MAYER, R. *Noções de Hidráulica Florestal*. Direcção geral dos serviços florestais e aquícolas. 1941.
FRY, J. R. Willows for streambank control. *Soil Conservation*, 4, p. 109-111, 1938.
PRÜCKNER, R. *Die Technik der Lebenden Verbauung und das Weidenproblem im Fluâbau und in der Wildbachverbauung*. 1948. 51 p.
AICHINGER, E. *Die Pflanzensoziologie im Dienste der Forstwirtschaft*. Berichte der Forstwirtschaftlichen Arbeitsgemeinschaft an der Hochschule für Bodenkultur in Wien, Folge 2. 1948.
HASSENTEUFEL, W. *Die Grünverbauung von Wildbächen*. Österreichische Wasserwirtschaft, Heft 12. 1950.

22 SCHIECHTL, H. M. *Grundlagen der Grünverbauung*. Mitteilungen... *Op. cit.*

23 KRUEDENER, A. *Ingenieurbiologie... Op. cit.*

24 KRUEDENER, A. & BECKER, A. *Forschungsstelle Für Ingenieurbiologie des Generalinspektors Für das Deutsche Strassenwesen*: Atlas Standortkennzeichnender Pflanzen. Berlin: forschungsstelle für ingenieurbiologie des generalinspektors für das deutsche strassenwesen, Wiking Verlag, 1941.
KRUEDENER, A. *Ingenieurbiologie... Op. cit.*

25 SCHIECHTL, H. M. *Grundlagen der Grünverbauung... Op. cit.*

26 PRÜCKNER, R. *Die Technik der Lebendverbauung*. Wien: Österreichischer Agrarverlag Wien, 1965. 200 p.

[27] KRUEDENER, A. *Ingenieurbiologie... Op. cit.*

[28] CORNELINI, P. & SAULI, G. *Manuale di indirizzo delle scelte progettuali per interventi di ingegneria naturalistica.* 1a ed. Roma: Ministerio dell' Ambiente e della tutela del territorio-Progetto Operativo Difesa Suolo, Istituto Poligrafico e Zecca dello Stato S.p.A. – Salario, 2005. 389 p.
CORNELINI, P. & SAULI, G. *Principi Metodi e Deontologia Dell'Ingegneria Naturalistica.* Roma: Regione Lazio e Associazione Italiana per la Ingegneria Naturalistica, 2012. 199 p.
CORNELINI, P. & FERRARI, R. *Op. cit.*

where technical and nontechnical soil bioengineering functions are clearly distinguished and identified.

Further its essential principle, the use of vegetation as construction material and structural element; soil bioengineering has three additional desirable guiding principles as hierarchized on figure 1. So far as a soil bioengineering intervention goes in the pathway given by these guiding principles the more it enhances a stable dynamic system. In other words, the number of degrees-of-freedom of the projected intervention is larger when more guiding principles are observed. A larger number of degrees-of-freedom implies in more possible dynamic equilibrium configurations when the system is faced down by natural or anthropic destabilization demands.

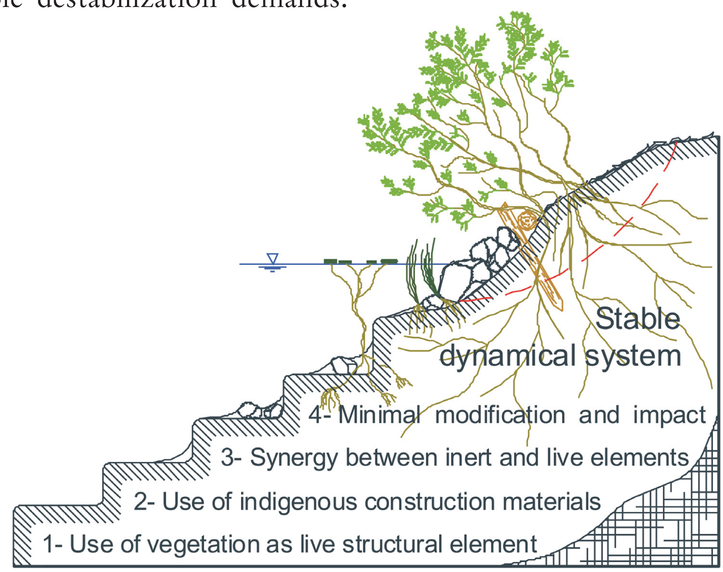

Figure 1: Soil bioengineering essential and guiding principles.

[29] GRAY, D. H. & LEISER, A. T. *Biotechnical Slope Protection and Erosion Control.* Van Nostrand Reinhold Company Inc., 1982. 271 p.
SCHIECHTL, H. M. & STERN, R. *Handbuch für naturnahen Erdbau*: Eine Einleitung für ingenieurbiologische Bauweisen. Wien: Österreichischer Agrarverlag, Druck und Verlagsgesellschaft m. b. H., 1992. 153 p.

It is also true that soil bioengineering measures has technical limitations regarding to their application,[29] in general soil bioengineering schemes are only assigned to small or medium scale problems. There are also limitations related to the vegetation developing requirements, such as environmental, soil and ecological conditions. Other limitation is that the structural behavior of a soil bioengineering measure is conditioned to the healthy condition of the vegetation.

The recognition of soil bioengineering as a separate engineering discipline and the fully understanding of its current stage depends directly of the comprehension of the modern engineering concept development process which is addressed in the following section.

Historical development of engineering concept

The engineering modern concept is greatly remarked by a conscious knowledge of the relevant behavior of natural phenomena related to a given design subject. Engineering today is considered, in a basic sense, the application of science to technological problems.[30]

For many years this concept had involved just a direct application of scientific results and discovers, without making any structural change in scientific principles. However, this model of interaction between science and practical application was substituted by recognition that technology has its own conceptual framework, which is parallel to, and indeed independent of scientific basic principles.[31] Actually, the science and practical application interaction requires the developmental of a distinct body of knowledge, commonly called engineering science.[32] However, this development took a long and nonlinear process over the centuries in the human civilization History.

By a considerable time, civil engineering disciplines had developed more or less independently of each other.[33] It was not until the second half of the eighteenth century that the engineering science proper came into existence.[34] Another engineering branches and disciplines are still developing such scientific framework. Even though, science as a distinct realm from engineering was not a purposeful activity of primitive peoples, one can find in history, evidences of a differentiation between two types of knowledge, a theoretical and a practical side. This separation was recognized by the ancient Greeks[35] and also by the romans[36]. The clear model of interaction between practical and theoretical knowledge gives way to the disclosure of engineering as a science branch. This model was initially proposed by the Scottish civil engineer William J. M. Rankine in the middle of 19th century.

According to Rankine[37] the mechanical knowledge may be distinguished into three types: purely scientific knowledge, purely practical knowledge and a third and intermediate one which relates to the application of scientific principles to practical purposes. Rankine model also proposes that this third kind of knowledge arises from understanding the harmony between theory and practice.

Engineering can be regarded, according Rankine model, as the art of practical application of scientific and empirical knowledge to the design and production processes.[38] According to Florman[39] is this middle position, the

30 FLORMAN, S. C. *The civilized Engineer*. New York: St Martin's Griffin, 1987. 272 p.

31 CHANNELL, D. F. The harmony of theory and practice: The engineering science of W. J. M. Rankine. *Technology and Culture*, 23, p. 39-52, 1982.

32 CHANNELL, D. F. *Op. cit.*

33 STRAUB, H. A. *Op. cit.*
ADDIS, B. *Op. cit.*
SAYÃO, A. *História da Engenharia Geotécnica no Brasil*: 60 anos da Associação Brasileira de Mecânica dos Solos e Engenharia Geotécnica. Rio de Janeiro: AMBS, 2010. 254 p.

34 STRAUB, H. A. *Op. cit.*

35 ADDIS, B. *Op. cit.*

36 VITRUVIUS, P. *The Ten Books of Architecture*. New York: Dover Publication, 1960. 331 p.

37 RANKINE, W. J. M. *Op. cit.*

38 KIRBY, R. S. *et al. Engineering in History*, McGraw-Hill, 1956. 544 p.

39 FLORMAN, S. C. *Op. cit.*

main contributor to the engineering progress, to credit the workshop as well the laboratory, the manual and intellectual labor, valuing intuition and experience, as well theory and experimentation. The main requisites of an engineering discipline in its modern conceptual framework can be grouped into three categories: professional practice, professional institution and professional training.

The engineering current professional approach has as its fundamental characteristic the use of numerical calculations and abstract mathematical concepts in the design process. The professional institution establishment is a key requisite of an engineering discipline to assume its modern framework. The professional institution consists basically of the formation of a community that shared certain skills and common body of knowledge, as well as values and a code of working. Engineering became defined, in the 17th and 18th centuries, by the body of knowledge that could be captured in books and by the formal means in which a person could train for and enter the profession. This instruction process relies on the fact that a person could learn engineering principles through books and classes, without the dependence of immediate personal experience. All contemporary engineers enter their profession by passing the portals of science.[40]

According to Straub[41] in the development of engineering disciplines, such as material and building science, three phases can be distinguished: the artisan stage, the descriptive stage and the quantitative stage. Is it true that no matter how closely modern engineering becomes identified with science, no matter how the end product of a engineering project seems remote and abstract, it can never be severed from its origins in craftsmanship.[42] But, the mark of distinction among the three phases is upon the instinctive approach. While an engineering discipline in the artisan stage relies mainly on intuition in a making-decision process, the quantitative or analytical phase is chiefly supported by a scientific based reflection process.

[40] FLORMAN, S. C. *Op. cit.*
[41] STRAUB, H. A. *Op. cit.*
[42] FLORMAN, S. C. *Op. cit.*

Artisan stage

The artisan acquires the knowledge of his profession through years of experience. His knowledge is purely empirical, gained from experience and handed down from person to person, no general theory is present and economic principles are absent. The artisan phase is marked by the collecting of data about what worked and what did not. However, the use of such empirical rules left little flexibility and excluded radical departures from precedent, making engineering progress a slow process.

The professional institution at an artisan stage is almost absent or very incipient. During this phase, craftsmen could banded together in guilds, and organizations,[43] but there is no regulatory agencies or design codes that served to protect the public as well the professional class. The artisan professional training process is the apprenticeship method. There is no technical school or textbooks. Such matters of a technical nature passed orally from generation to generation of craftsmen.[44]

[43] FLORMAN, S. C. *Op. cit.*

[44] KIRBY, R. S. *et al. Op. cit.*

Descriptive stage

The descriptive stage is marked by the appearing of condensed rules regarding the qualitative behavior and requisites of a given engineering task. Through not exclusively based on scientific principles, these rules, after all, represent an application of elementary scientific knowledge. They give general advice to the builder such as the most favorable cutting season for wood, in the renaissance.[45] In the same purely descriptive manner, stones in construction engineering were classified merely according to geographical principles, denoting a strong regionalism on the standardization process of descriptive stage, or even according to their color, revealing only aesthetical preoccupation, but not according to engineering properties such as strength in a quantitative sense. Master buildings knew the limitation of their materials, and much of their experience could be codified and passed to others as design rules or design procedures, but just in a descriptive manner or in a how-to-do procedure.

[45] STRAUB, H. A. *Op. cit.*

As in the artisan stage the engineers focused more in answer the questions how to attain determined engineering tasks than to understand the relevant phenomena underling their decisions. The result is that the descriptive design rules are of not general application, being, in general, inconsistent when extrapolated.

On the descriptive stage there is still no professional infrastructure: no committees reviewing design codes of practice, and no technical press through which scientific developments were communicated to practicing engineers. The professional training in a descriptive stage of a given engineering discipline is characterized by the use of the first technical manuals of instructions. In general, those works combine rules of thumb with mathematical or even theoretical descriptive concepts.[46] During the early 19th

[46] FLORMAN, S. C. *Op. cit.*

century, the theoretical, scientific approach for many engineering problems was gradually beginning to be taken for granted. The change from artisan routine to modern scientific based engineering must be regarded as truly revolutionary, when the analytical, quantitative stage of a given engineering discipline is reached. It marks the beginning of a unique and important development.[47]

[47] STRAUB, H. A. *Op. cit.*

Quantitative stage

The analytical or quantitative stage in many civil engineering branches was stimulated by the confluence of the scientific discoveries and the economic requirement of the use of resources and materials in the engineering practice during 18th century.[48] The strength of materials and structural engineering had become quantitative disciplines late on the same period.[49]

[48] PETROSKI, H. *To Engineer is Human* – The role of failure in successful design. New York: Vintage Books, 1992. 272 p.

[49] STRAUB, H. A. *Op. cit.*

By this time many engineers had developed confidence in design techniques based on calculations rather than empirical data alone. However, it should not be expected that the model would accurately represent every aspect of a real world structure. Rankine in middle of nineteenth century proposed the concept of the now largely used factor of safety to express the difference between the conceptual theoretical model and the real structure.[50]

[50] ADDIS, B. *Op. cit.*

The design process in its modern sense is more focused on universal and general application, eliminating regionalisms and being not restricted to imitate previous specifications. The design procedure in the analytical sense is much more than a set of instructions to construction workers. In current language it is a mathematical model of the building – an abstract representation of the structure that allows one to experiment, to try out ideas without actually executing them.

Engineering science grew out of and in the university environment. In general, the introduction of technology into the university curriculum came at the same time of active interest in the professionalization of engineering.[51] The emergence of engineering as a profession brings the realization of the importance of scientific and technical education as a prerequisite for engineering. The modern engineer education concept means that a person can derive and understand engineering subjects such as structures and machines, without, having been a builder himself.

[51] CHANNELL, D. F. *Op. cit.*

The analytical stage also enables the elaboration of design codes. Being produced by leading members of each profession and given a government's stamp of authority, design codes represent a distillation of engineers' collective experience in a certain field. They are intending to ensure that, by using them, any competent engineer will be able to arrive at a satisfactory design and to achieve the level of confidence in a proposed design that society considers acceptable. Quantitative engineering facilitates the precise stipulations regarding the quality, origin and treatment of the building materials to be used, as also the construction program, and site organization, legal and financial clauses.

The synthesis of freely creative design and analytical approach is the foremost symbol and criterion of modern engineering and it is the main reason for its perennial progress.

Soil bioengineering as an engineering discipline

Soil bioengineering has as its major objective to project an stable dynamic ecosystem[52] that can directly contributes to improve the geotechnical, hydraulic and hydrological conditions of a given site,[53] or in other words to facilitate or even to enhance the stabilization of natural systems. Even though the key elements in this project action are live organisms such plants, the backbone of soil bioengineering as a science branch is its engineering approach, or using the words of Petrone & Preti,[54] the constitution of a technical-scientific discipline. Early descriptions of soil bioengineering as a science discipline had point out this principle, as it can be viewed on the Kruedner[55] work when referring to soil bioengineering projects as actions were the physical laws of "hard" engineering are used in confluence to the biological attributes of living material.

Soil bioengineering has additional functions aside this technical or engineering finality but, soil bioengineering is not a landscaping approach or even just a construction method. The very essence of soil bioengineering relies on the development of its methodological frame and systematic and scientific study of its applications.[56] Terms such vegetative construction, biological building material,[57] live building material[58] are clear indicators that when one is dealing with soil bioengineering approaches is working over engineering ground. The live plant material is not employed as decorative or cosmetic intervention, but clearly as a civil engineering work.[59] Plants are used as building material in the soil bioengineering interventions and consist of the base of such works, making appropriated its name as a civil engineering branch.

52 MORGAN, R. P. C. & RICKSON, R. J. *Op. cit.*

53 LI, M. & EDDLEMAN, K. E. Biotechnical engineering as an alternative to traditional engineering methods: A biotechnical streambank stabilization design approach. *Landscape and Urban Planning*, 60, p. 225-242, 2002.

54 PETRONE A. & PRETI F. Soil bio-engineering for risk mitigation and environmental restoration in a humid tropical area. *Hydrology and Earth System Sciences*, 14, p. 239-250, 2010.

55 KRUEDENER, A. *Op. cit.*

56 LACHAT, B. Conserver, aménager, revitaliser les cours d'eau avec une logique naturelle. *Annales de Limnologie-International Journal of Limnology*, 34, p. 227-241, 1998.

57 SCHIECHTL, H. M. & STERN, R. *Ground Bioengineering Techniques... Op. cit.* SCHIECHTL, H. M. & STERN, R. *Water Bioengineering Techniques*: For Watercourse Bank and Shoreline Protection. Wiley, 1997. 208 p.

58 LACHAT, B. *Op. cit.* DE ANTONIS, L. & MOLINARI, V. M. *Manuale di Ingegneria Naturalistica*: Nozioni e tecniche di base. Regione Piemonte, Servizio a cura della Direzione Opere pubbliche Difesa del suolo, Economia montana e foreste, 2007. 389 p.

59 LACHAT, B. *Op. cit.*

Still in accordance to Lachat[60] soil bioengineering is not infrequently erroneous seen just a plantation or a landscape activity. Being used alone or as an essential complementary approach to traditional engineering solutions,[61] soil bioengineering practice definition clearly includes its final goal: to fulfill engineering functions[62].

Such as any correlated engineering discipline soil bioengineering has additional concerns than just construction methods, according to Gray & Sotir[63] soil bioengineering and biotechnical methods also can be viewed as strategies or procedures for minimizing the liabilities of vegetation while capitalizing on its benefits. In this context, according to Lachat[64] soil bioengineering is comprised, in the set of solutions, methods and approaches available to the engineer in order to obtain functional and durable solutions. The search for safety, economy and feasibility is universal among engineering branches and it is not absent in soil bioengineering applications.

The claim that soil bioengineering is not an exact science,[65] but rather it is an art that must be designed from many different factors that are not always easy to determine is not false but it is completely true for every traditional engineering branch. As exposed on the previous section, engineering has developed it proper scientific frame, and its branches tend to pass from the artisan stage to an analytical phase. This path is not different regarding soil bioengineering as illustrated in the Bentrup & Hoag affirmation: "Some of the [soil bioengineering] techniques will work well in one situation, but not in others. The secret is to learn over time and many different projects."[66]

According to Gray & Sotir[67], plant materials are not different from other materials in the sense that they must be selected with care for their intended purpose, which once more affirms the engineering character of biotechnical methods. However, the very singular nature of this construction material[68] turns necessary the development of an engineering discipline capable to deal with the vegetative material peculiarities. In this sense plant material are seen not only in biological or ecological senses as the traditional point of view of botanic or biological sciences but, also as building material and engineering structures.[69]

The development process of soil bioengineering as a separated branch of civil engineering can be regarded as a rediscovery and a reinterpretation of traditional engineering methods.[70] In some cases it can be necessary that an entirely new approach must be created in order to fulfill

60 LACHAT, B. *Op. cit.*

61 GRAY, D. H. & SOTIR, R. B. *Op. cit.*

62 LAMMERANNER, W.; RAUCH, R. P. & LAAHA, G. Implementation and monitoring of soil bioengineering measures at a landslide in the Middle Mountains of Nepal. *Plant and Soil*, 278, p. 159-170, 2005.

63 GRAY, D. H. & SOTIR, R. B. *Op. cit.*

64 LACHAT, B. *Op. cit.*

65 BENTRUP, G. & HOAG, J. C. *The Practical Streambank Bioengineering Guide*. United States Department of Agriculture, 1998. 150 p.

66 BENTRUP, G. & HOAG, J. C. *Op. cit.*

67 GRAY, D. H. & SOTIR, R. B. *Op. cit.*

68 DE ANTONIS, L. & MOLINARI, V. M. *Op. cit.*

69 DUPUY, L.; FOURCAUD, T. & STOKES, A. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant and Soil*, 278, p. 119-134, 2005. HAMZA, O. *et al.* Novel biomechanical analysis of plant roots. p. 13-20. *In*: STOKES, A. *et al. Eco-and Ground Bio-Engineering*: The Use of Vegetation to Improve Slope Stability, 2007. STANGL, R. Hedge brush layers and live crib walls – stand development and benefits. p. 287-296. *In*: STOKES, A. *et al. Eco-and Ground Bio-Engineering*: The Use of Vegetation to Improve Slope Stability, 2007.

70 PETRONE A. & PRETI F. Soil bio-engineering for risk mitigation and... *Op. cit.*

the vegetative peculiar requirements. The differences in approach are also a remarkable distinction about soil bioengineering and other civil engineering branches.[71] According to Lachat[72] soil bioengineering consists of a nature emulation, artificially accelerated to fulfill mainly technical requirements but also to accomplish economical, ecological, and aesthetics functions. In fact soil bioengineering requires both an understanding of engineering principles and knowledge of vegetation[73], but not in a detached manner. It requires an understanding of how these two branches of knowledge interacts one with another and the way which both interacts with soil, water and climate conditions of a given work site, what turn soil bioengineering a very interdisciplinary engineering branch.

Current stage and practice

The most salient aspect of soil bioengineering is the use of live plant materials as an active element in the intervention. To achieve such finality, local or even autochthonous vegetal species must be found. However, the properties and features desirable for such vegetative material are of universal character, they are called biotechnical characteristics. The lacking of information regarding local species with biotechnical characteristics is frequently a prominent obstacle in the soil bioengineering techniques spreading. This search for local species has caused, at least apparently, some misunderstanding about the nature of soil bioengineering itself. It is usual to find in the soil bioengineering specified literature works whose content and even the proper title seems to validate their information only locally.[74]

The question is: is the universal validity of the technique being clouded with the necessity of local vegetable species with biotechnical properties? Even though some degree of confusion about this aspect can happens, it can be properly cleared by considering the soil bioengineering definition made by virtually each author, all of them have been emphatic to view vegetation as a constructive material. In other words, just the materials – what is the same in almost any engineering branch – are of regional character, the design processes must have an analytical methodology of universal validity character. The regionalism regarding soil bioengineering technical applications can be originated not only from this confusion but also from the proper current stage of this discipline.

[71] LEWIS, L. *Op. cit.*

[72] LACHAT, B. *Op. cit.*

[73] COPPIN, N. & RICHARDS, I. *Use of vegetation in civil engineering*. Construction Industry Research and Information Association. CIRIA, 1990. 312 p.

[74] FLORINETH, F. Begrünungen von Erosionszonen im Bereich über der Waldgrenze. *Zeitschrift für Vegetationstechnik*. 5, p. 20-24, 1982. BORGHERO, G. *et al. Lignes directrices pour l'apllication du genie écologique et de bonnes pratiques de gestion du territoire en milieu méditerranéen*. Commission Européenne, 2003. 430 p. PUGLISI, S. *Progettazione di aree verdi e ingegneria naturalistica in ambiente mediterraneo*. Editoriale Bioss s. a. s. Castrolibero, 2004. 336 p. PETRONE, A. & PRETI, F. *Ingeniería naturalística en Centroamérica... Op. cit.* PETRONE, A. *Op. cit.* SUTILI, F. J. & ANDRAE, F. Wie Waldbesitzer in Brasilien zur Nachhaltigkeit verdammt werden. *Forstzeitung*, Viena/Áustria, 112, p. 16-17, 2001. SUTILI, F. J.; DURLO, M. A. & BRESSAN, D. A. Potencial biotécnico do sarandi-branco (*Phyllanthus sellowianus* Mull. Arg.) e vime (*Salix viminalis* L.) para revegetação de margens de cursos de água. *Ciência Florestal*, 14, p. 13-20, 2004. SUTILI, F. J. & DURLO, M. A. Bioengenharia de solos: o estado da arte na Europa e no Sul do Brasil. *Conselho em Revista CREA-RS*, Porto Alegre - RS, p. 31, 2007. QUINTANA, Y.; PETRONE, A. & PRETI, F. *Op. cit.*

Soil bioengineering current stage is not uniform regarding all its various sub-branches, since they are not equally developed.[75] However, considering the principles presented on section 3, the artisan and descriptive marks can be identified in soil bioengineering regarding its professional practice, institution and training.

Professional practice

In spite of embrace a sufficient set of basic principles in order to characterize a distinguished approach, soil bioengineering professional practice does not exhibit a standardization degree comparable to other correlated engineering branches. The professional approach facing a practical problem depends massively on the previous experience of each engineer.

Regarding technical codes, soil bioengineering works lack an analytical point of view and are strongly based on practically accumulated previous experience. This could be identified on expressions such as: "gained experience"; "new experience developing and accumulation"; which are recurrent in the disclosure period of soil bioengineering as a scientific discipline[76] and are kept at the present time[77]. Coppin & Richards[78], and also Hacker & Johannsen[79] precisely recognize the artisan origin of soil bioengineering techniques, and also its "gained experience" approaching. Even the plant species selection at the current stage depends on the previous experience of the professional.

The concept of an optimized design (safety, economic and feasible) is present and cleared pointed out by the technical literature, Cornelini and co-workers[80] emphatically present those principles in schemes showing a clear distinction between design and deontological mistakes. However, the lacking of analytical approach could confuse the engineer or other professional engaged in a soil bioengineering project, leading him, not infrequently, to an only cost-oriented design (in opposition to a performance-based design). The soil bioengineering professional practice is thus characterized by the lacking of technical specification, design codes, monitoring procedures and maintenance standardized methodologies.

The novice engineer who desires to employ soil bioengineering methods must search a solution based on the encoded (by the yet experienced professionals) information founded in schemes or entirely descriptive procedures such as tables, decision trees, graphs, or texts that guide the

[75] MORGAN, R. P. C. & RICKSON, R. J. *Op. cit.* GRAY, D. H. & SOTIR, R. B. *Op. cit.*

[76] KRUEDENER, A. & BECKER, A. *Op. cit.* KRUEDENER, A. *Op. cit.* SCHIECHTL, H. M. *Grundlagen der Grünverbauung. Op. cit.* PRÜCKNER, R. *Die Technik der Lebendverbauung... Op. cit.* PIETZSCH, W. *Ingenieurbiologie*. Verlag von Wilheim Ernst & Sohn, 1970. 119 p.

[77] LACHAT, B. *Op. cit.* FLORINETH, F. *Pflanzen Statt Beton*: Handbuch Zur Ingenieurbiologie Und Vegetationstechnik. Berlin und Hannover: Patzer Verlag, 2004. 272 p. DURLO, M. A. & SUTILI, F. J. *Op. cit.* FERNANDES, J. P. & FREITAS, A. F. M. *Introdução à Engenharia Natural*. v. 2. Portugal: EPAL – Empresa Portuguesa das Águas Livres S. A., 2011. 108 p.

[78] COPPIN, N. & RICHARDS, I. *Op. cit.*

[79] HACKER, E. & JOHANNSEN, R. *Ingenieurbiologie*. Stuttgart (Hohenheim), 2012. 336 p.

[80] CORNELINI, P. & SAULI, G. *Manuale di indirizzo delle scelte progettuali... Op. cit.* CORNELINI, P. & FERRARI, R. *Op. cit.* CORNELINI, P. & SAULI, G. *Principi Metodi e Deontologia... Op. cit.*

beginner engineer to a closed solution, without exposing the underlying analytical method (if existent).

Regarding the inert material specifications the task is obviously facilitated by the traditional engineering knowledge, and once more the difficulty relies on the vegetative material whose quantitative specification information is almost inexistent, and also its interaction with the inert materials. There is also ignorance about the forces magnitude and dimension scales with the soil bioengineering can handle. The underlying processes and correlated phenomena are qualitatively understood and satisfactorily described by the technical and scientific literature; however the quantitative description of some needed design parameters is yet very incipient. One of the main reasons for these characteristics is the very erratic and complex behavior and mechanisms that characterize vegetation itself as well its interaction with the various environmental agents such soil, climate, landscape and other living organisms.

Professional Institution

In the context of professional institution, soil bioengineering has the support of universities which are interested on this scientific area, including some research institutes dedicated to the soil bioengineering developing. National and local professional associations are common in some European Countries and in the USA. Official and governmental agencies, especially those related to hydric resources and road engineering has demonstrated interest and has contributed for the soil bioengineering development. However, the existing organisms have not yet the sufficient acting amplitude, organization and authority to be in charge of the analytical standardization of soil bioengineering practice. The regulatory agencies in charge of soil bioengineering activities do not possess, in most countries, specified codes or standards regulations to supervise these activities.

Academic research efforts in terms of analytical knowledge have already being done.[81] Even though these efforts are an important contribution to the developing of soil bioengineering they are not uniform. In addition, those studies do not present common or standard methods regarding technical knowledge sharing, acting conduct, and tests protocols. Nowadays soil bioengineering has its own publishing and propagation mechanisms. Its results can reach the interested public through scientific journals specialized in the correlated themes. There is also publica-

[81] GERSTGRASER, C. *Ingenieurbiologische Bauweisen an Fliessgewässern*. Grundlagen zu Bau, Belastbarkeiten und Wirkungsweisen. Dissertationen der Universität für Bodenkultur in Wien, Band 52. Wien: Österreichischer Kunst- und Kulturverlag, 2000. 92 p.
RAUCH, H. P. *Hydraulischer Einfluss von Gehölzstrukturen and Beispiel Einer Ingenieurbiologischen Versuchsstrecke Am Wienfluss*. Dissertationen Der Universität Für Bodenkultur in Wien, Band 63. Wien: Guthmann-Peterson, 2006. 188 p.
HAMZA, O. *et al. Op. cit.*
STOKES, A. *et. al.* Mechanical resistance of different tree species to rockfall in the French Alps. *Plant and Soil*, 278, p. 107-117, 2005.
VAN BEEK, L. P. H. *et al.* Observation and simulation of root reinforcement on abandoned Mediterranean slopes. *Plant and Soil*, 278, p. 55-74, 2005.
WU, T. H. Root reinforcement: analyses and experiments. p. 21-30. *In*: STOKES, A. *et al. Eco- and Ground Bio-Engineering*: The Use of Vegetation to Improve Slope Stability, 2007.
SUTILI, F. J. *et al.* Flexural behavior of selected riparian plants under static load. *Ecological Engineering*, 43, p. 85-90, 2012.

tions specialized exclusively on soil bioengineering subjects, and scientific events such congresses, symposiums and technical forums. Regarding propagation as well other institution issues it can be observed a large progress in the current stage of soil bioengineering. Possibly, the next important step in this process is the creation of an international organization able to gather different regional organizations.

Professional training

The professional training in soil bioengineering field is highly influenced by both currently professional practice and institution. Due to the very current stage of the professional practice the soil bioengineering learning process depends massively upon the direct contact with the practical professional exercise. The technical books also reflect this fact by valorizing, in most cases, the knowledge transferring by practical experience description or even giving executive guidelines, showing in the training process the same non-analytical behavior of the professional practice and institution.

The formal educational system composed by universities and institutes strive to make the learning process more analytical, but the tools to attain such goal are not completely available. There is not a minimum standard curriculum, not even in a regional degree, related to soil bioengineering professional training. The major part of specialized books on the subject consists of technical handbooks and not textbooks of general application.

Soil bioengineering, is currently characterized by an artisan-descriptive phase, which is very natural in the developing process of every engineering branch. This current stage could not be absolutely understood as a failing process or weakness feature. But, similarly to even other engineering discipline, this phase must be overcome and the signs toward this analytical direction can be yet seen. In the following section the consequences of such developing process are discussed in details.

The main challenges

Even though soil bioengineering techniques compound an alternative approach or complementary actions to the traditional civil engineering methods they are not equally accepted in engineering applications. The schemes and intervention in soil bioengineering methods are, in many places, little known or even completely ignored. The reasons of these reluctance and ignorance could be largely explained by the current stage regarding professional practice, institution and training as discussed in the previous section.

Considering the professional practice field, one of the great obstacles to the soil bioengineering techniques broader acceptance is the scarce information regarding vegetation species with detected biotechnical potential. The knowledge gap regarding local vegetation's biotechnical properties generally obligates the engineer to choose between two paths: the use of allochthonous species or the prioritization of non-vegetative intervention schemes such as geotextiles, erosion control blanket, concrete, gabions and other inert structures, where vegetation effect is regarded to a secondary role,[82] not infrequently, without any technical function.

Following the premises from the very first soil engineering definitions[83], the vegetation used in its techniques should be, preferentially, autochthonous and must be employed as an active structural component contributing directly to soil stabilization. Here, the term stabilization is used in its broader sense, meaning, according to Sowers & Sowers[84], the process of improving soil in order that it can meet the desirable engineering requirements.

According to Cornelini & Ferrari[85] the autochthonous material use is of fundamental character to a given intervention using soil bioengineering technique. This fact means that even though soil bioengineering ecological function is not technically a restrictive requirement, it is an important principle in the discipline practice. The economical and aesthetical functions can be regarded on the same way. This kind of separation is really necessary and central to the analytical development of the soil bioengineering since it can guide the engineer to the needed functions on a specific project.

According to Morgan & Rickson[86] when a soil bioengineering based intervention is designed, it comprises further than a traditional engineering work but also an ecosystem. By the other hand, according to Gray & Sotir[87] the live plant materials are not different from other conventional material, in the sense that they should be selected and specified according the intentioned purposes in the intervention design. Hence, the identification of biotechnical properties and botanical related characteristics in the autochthonous flora of a given local is an important step to

[82] COPPIN, N. & RICHARDS, I. *Op. cit.*

[83] KRUEDENER, A. & BECKER, A. *Op. cit.* SCHIECHTL, H. M. *Grundlagen der Grünverbauung. Op. cit.*

[84] SOWERS, G. F. & SOWERS, G. B. *Introductory Soil Mechanics and Foundations*: Geotechnical Engineering. New York, 1979. 621 p.

[85] CORNELINI, P. & FERRARI, R. *Op. cit.*

[86] MORGAN, R. P. C. & RICKSON, R. J. *Op. cit.*

[87] GRAY, D. H. & SOTIR, R. B. *Op. cit.*

develop soil bioengineering as a more analytical discipline. The great challenge related to this issue is the very absence of a program to structure methodologically the recognition and search for determined local species with the desirable biotechnical properties to enhance a given necessary property to dynamically stabilize natural system. Such a methodology is really important, since according Schiechtl[88] in a given floristic area there are many appropriated species to use in landscaping or horticultural activities, but there are few which prove their biochemical value. In the absence of such analytical methodology to search, to measure and to quantify biotechnical potential in vegetation species, the results could be inconsistent or demand a larger amount of time to be considered consistent.

[88] SCHIECHTL, H. M. *Sicherungsarbeiten im Landschaftsbau*. Grundlagen – lebende Baustoffe – Methoden. München: Callwey-Verlag, 1973. 244 p.

This lack of analytical approach also leads to a gap in the conscience concerning the real reach of soil bioengineering interventions, regarding engineering problem dimensions. It can be observed in the stamen done by Cornelini & Sauli[89] who predict an increasing in the soil bioengineering application reach as the plant biotechnical properties knowledge also increases. Along these lines, the very current reach horizon of soil bioengineering is let obscure.

[89] CORNELINI, P. & SAULI, G. *Principi Metodi e Deontologia... Op. cit.*

The incomplete methodological and analytical focus at the current soil bioengineering professional practice transcends the search and identification of biotechnical valuable species and is also present in the intervention scheme choice and design process. The existed models are strongly based on previous and empirical experience. Those models could in some level incorporate some scientific knowledge, however, without a complete analytical and quantified design process. The main difficulties, resulted from this empirical design process, are that new schemes are, at least partially, relegated to the experimental range. When the engineer faces a completely new problem or application he has not the necessary analytical tools to extrapolate his previous knowledge to the new situations. Such a lack of analytical approach is according Lewis[90] one of the fundamental difficulties to establish the professional field of soil bioengineering.

[90] LEWIS, L. *Op. cit.*

The main consequence of such empirical design process is reflected on the great variety of soil bioengineering intervention results. It can be found some soil bioengineering projects which fail from a technical aspect, being not able to convey appropriately the imposed requirements. On the other hand there are interventions exaggeratedly conservative, consisting of, in the words of Cornelini

& Ferrari[91], a case of deontological error. According to Rankine[92] this conservative approach is a direct result of the unscientific design which is obligate to counteract the lack of analytical knowledge by the use of massive strength materials and schemes.

Soil bioengineering does not feature those abstract methods of design. According to Morgan & Rickson[93], without engineering quantification, vegetation cannot be included even in a simple way in engineering design procedures. The result is that soil bioengineering has its solutions largely based on the qualification of a mentor artisan (in a similar way to the master buildings in middle age). The term artisan is used here meaning a professional who is guided essentially by his intuition. Therefore, is the intuition, the key mark which distinguishes the engineer from the artisan, both have it, but just the last is uniquely and essentially oriented by intuited insights.

Soil bioengineering professional institution is marked by the scarce existence of literature, codes of practice, or regulation.[94] This current stage limits the prescription of these techniques on the design procedures. Other important consequence is the lack of confidence by the engineer to forecast performance at a safety level during the work lifetime, which in turn leads this same professional to reject such interventions. These challenges follows from the fact that the recourse to empirical design procedures means that it is impractical to specify limits for loadings or factors of safety in the engineering design process.

Regarding soil bioengineering training aspects, the current empirical stage prevents that both the learning and knowledge acquiring processes used on standard engineering courses could be replicated and adapted to this new engineering field. This is explained by the fact that an artisan and empirical knowledge request more practice and field experience than an analytically developed engineering branch.

It is important to note that if an intervention is based just on artisan and descriptive criteria, this not means that is an inferior solution in terms of quality. On descriptive phase of structural engineering many buildings such as the middle age gothic cathedrals, had a structural quality that hardly could be improved by the modern engineer.[95] However, regarding to its fundamental descriptive characteristics the constructive techniques of such buildings were only ruled by the master building. Furthermore, those techniques were not unique and change from master to

[91] CORNELINI, P. & FERRARI, R. *Op. cit.*

[92] RANKINE, W. J. M. *Op. cit.*

[93] MORGAN, R. P. C. & RICKSON, R. J. *Op. cit.*

[94] MICKOVSKI, S. B. & Van BEEK, L. P. H. Decision support systems in eco-engineering: the case of the SDSS. p. 231-238, *In*: STOKES, A. *et al. Eco- and Ground Bio-Engineering*: The Use of Vegetation to Improve Slope Stability, 2007.

[95] STRAUB, H. A. *Op. cit.*

master. Those characteristics result in a very expensive knowledge appropriation and also in a very irregular knowledge transmission. Another negative consequence is the effort repetition and in many cases, a trial and error sequence which turns the very developing process a very cumbersome procedure.

In a similar way that happened to other engineering disciplines, the quantitative and abstract marks from analytical phase can open new possibilities that are previously unimaginable to soil bioengineering. While most engineering branches have as their main issues to answer "why" questions, soil bioengineering could not be restraint at every new challenge to answer only "how" questions, waiting for a long time until these new techniques become full established and accepted though the experience acquiring process.

Those difficulties should be appropriately addressed by an analytical approach, universally valid method, according the engineering premises and be not codified into subjective descriptions or dependent on experiment repetition or even closed on the artisan's mind. This structured an analytical approach could stimulate the interest of and encourage engineers and others to employ such soil bioengineering measures. In the next section a program to structure the soil bioengineering developing as a more analytical discipline is suggested and discussed.

Developmental program

Since soil bioengineering constitutes a branch or a discipline of the traditional engineering, a similar path to its development can be traced. The improvement of soil bioengineering could be granted by both scientific progress and technical evolution.[96] A parallel to the correlated traditional science branches is not only efficient to characterize and to provide understanding about the developing phases of the current stage of soil bioengineering. It could also be used to reduce the time required to this discipline reaches an analytical stage. According to Morgan & Rickson[97] the waiting for decades to new soil bioengineering schemes become full established and the techniques completely evaluated can be avoided by stating the potential of soil bioengineering as science and justifying the techniques involved to practitioners. In other words, by developing it as an analytical science field. This approach corresponds to the very definition of engineering as a link between theoretical scientific knowledge and technical practical application. In

[96] CORNELINI, P. & FERRARI, R. *Op. cit.*

[97] MORGAN, R. P. C. & RICKSON, R. J. *Op. cit.*

this way, the analytical setting of soil bioengineering, could be attained by appropriation, adaptation or even inspiration derived from all methodologies, practices, tests, protocols, procedures, and approaches that has being gradually evolved in the long developing process of correlated traditional engineering branches. This parallelism must be very regardful to specific particularities of soil bioengineering, mainly concerned to vegetative material and the additional finalities of its application such aesthetic, environmental and productive use of the intervention subjected area.

Even though plants constitute a very different material from those inert materials traditionally used in engineering building practices, vegetation, according to Schiechtl & Stern[98], as well any other building material must comply with origin conditions, quality characteristics, size, and age in order to appropriately perform or support the engineering properties improvement of soil.

The very first step to compose such parallelism between soil bioengineering and correlated traditional engineering branches is to understand clearly how some determined plant species could enhance some soil engineering properties. For example, according to Genet and co-workers[99], if root system characteristics, which govern soil stabilization, could be better identified, screening of suitable species for use on unstable slopes would be more efficient. This identification process itself could be clear and broadly applied to other technical actions of soil bioengineering by means of a model, as showed in figure 2, which correlates at one side the stabilization requisites of the natural system, which implies the technical function of soil bioengineering, and at the other side the inherent vegetation characteristics, the so called botanic characteristic. The interlink between these two classes of properties is performed by means of biotechnical constitution[100] or biotechnical properties[101].

In addition to the technical function consisting of improving natural systems physical stabilization, soil bioengineering has aesthetic, ecological and economical (since a soil bioengineering work can provide live vegetative materials to other interventions) finalities as showed in figure 2. It can also be used as source of other agricultural and forestry materials. This multifunctional character is, in several applications, a very useful feature[102] which cannot be paired, in most cases, by correlated traditional engineering techniques. As a construction material, live material, has some requirements to keep itself active since its insertion on soil bioengineering schemes until the entire intervention

98 SCHIECHTL, H. M. & STERN, R. *Water Bioengineering Techniques... Op. cit.*

99 GENET, M. *et al*. The influence of cellulose content on tensile strength in tree roots. *Plant and Soil*, 278, p. 1-9, 2005.

100 SCHIECHTL, H. M. & STERN, R. *Water Bioengineering Techniques... Op. cit.*

101 DURLO, M. A. & SUTILI, F. J. *Op. cit.*

102 EVETTE, A. *et al*. History of bioengineering techniques for erosion control in rivers in Western Europe. *Environmental Management*, 43, p. 972-984, 2009.

life cycle. Such requirements include ecological (soil, water and light conditions) and phytosociology (competition and interrelationship among species) requisites.

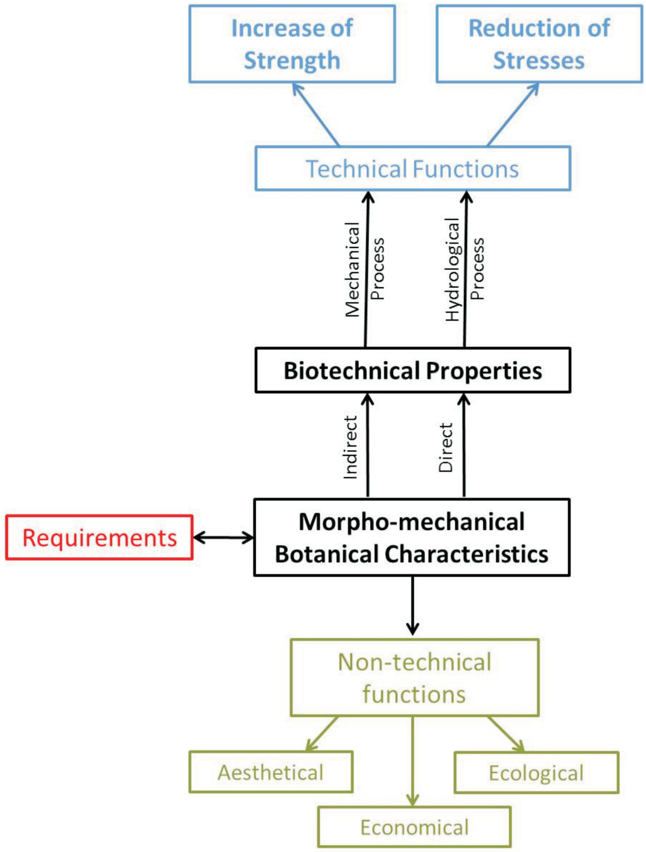

Figure 2: Correlation mode between live material construction and soil bioengineering functions.

The correlation model briefed in figure 2 can also clarify some concepts that, not infrequently, are mixed up. A brief literature survey in the soil bioengineering field is sufficient to reveal that not unusually; concepts such as finalities, functions, actions, properties, characteristics, approaches, techniques and schemes are not properly stated and distinguished in a rational way. It is also frequent that some causes and consequences are taken equally in a given list of properties or actions. It is also pertinent to propose a specified soil definition in the soil bioengineering perspective which share, but being not restricted to, the civil engineering approach to soil as a physic-chemical construction material and also having in common the productive and fertile point of view held up by agricultural sciences.

The biotechnical properties of a given vegetation specie or a group of plant species are those properties which can influence positively the soil engineering requisites. The action exerted by the biotechnical properties of vegetation upon soil engineering requisites could be classified in three classes according to the produced effects: mechanical, hydraulic and hydrological processes.[103] In general, effects of more than one group occur at same time.

[103]MORGAN, R. P. C. & RICKSON, R. J. *Op. cit.*

The positive influence on the natural system stabilization could be exerted in a direct way, by improving the inherent soil properties, or the system strength, such as the reinforcement in soil matrix due some soil root systems. And also, it could be performed in an indirect way, by reducing the demand action of destabilizing agents, such as reducing runoff volume by evapotranspiration or infiltration.

On the other side the botanical characteristics are inherent to the plants themselves, describing their behavior in terms of ecology, physiology and morphology, which in combination; result in the biotechnical properties of such vegetation. As an example a given root system architecture, which is a botanic characteristic, could result in more or less pull-out resistance. The parallelism to a given inert material used in traditional interventions could be traced in such a way that the botanical plant characteristics are related to the biotechnical properties in the same way as the inert materials characteristics (gravity, elastic modulus, etc.) are to the technical their properties (strength, stiffness, etc.).

The biotechnical vegetation characteristics should be sought according a primordial purpose. This objective is the fulfillment of the technical finality of soil bioengineering. The soil engineering requisites are enhanced by the biotechnical plant properties, which in turn are explained by a proper set of inherent botanical plant characteristics.

A clear model which translates inherent plant characteristics into enhancing of desirable soil engineer requisites is, in the view of the authors, the very first step to the evolution of soil bioengineering from its current artisan-descriptive stage to a more analytical one. This model can be obtained by the following basic steps:

Step 1: This step consists basically of the specific identification of all engineering requisites regarding interventions of soil bioengineering, the identification of all biotechnical properties that influence or contributes to the enhancement of these engineering requisites; and the identification of morpho-mechanical botanical characteristics responsible, directly or indirectly by the biotechnical properties. Then, this step is completed by the derivation of a correlation model, between engineering requisites and plant inherent characteristics, which make possible a clear understanding to derive the strategies and approaches of the next suggested steps

Step 2: The main goal of this step is to study how the engineering requisites surveyed on Step 1, are enhanced by conventional construction materials and traditional engineering techniques. And also to study the analytical quantification of the biotechnical properties surveyed on Step 1. This step consists of a fully understanding of both traditional techniques and the yet developed efforts to quantify the biotechnical properties, making possible to determine, what methods could be directly used or inspire the same kind of developing regarding soil bioengineering practices, and what new procedures needed to be derived.

Step 3: This step has as its main goal to rank the biotechnical properties collected on step 1 according to their developing necessity regarding step 2. This rank considers further the current developing stage of the biotechnical properties and also their amount of influence on soil engineering requisites. Is also considered the interdependence between those properties, since some of them must need the prior developing of others. This step leads to a rational program in terms of resources and time to develop analytically the soil bioengineering. This is achieved by defining what traditional approaches could be applied to the prioritized biotechnical properties. And also by defining those properties whose quantification method must be developing completely aside the traditional techniques. This step makes possible to determine the biotechnical properties whose parameters quantification could be follow a related traditional counterpart and those whose path need to be entirely developed according to the peculiarities presented by the live vegetative material. It includes the development of standard protocols regarding search of plants with biotechnical properties following the correlation, turning the species search activity an analytical procedure such in the case of other conventional construction materials. This is achieved, mainly, by focusing on principles and making these procedures of general and universal application instead of local oriented practices and regionalisms.

This model contributes to the main applicability requisites of soil bioengineering, which are, according to Gray & Sotir[104]: availability, installation feasibility, familiarity, techniques propagation and dissemination, design codes existence, and specification acceptance.

[104]GRAY, D. H. & SOTIR, R. B. *Op. cit.*

Both availability and installation feasibility are intimate related to the actual lacking knowledge regarding the local vegetation biotechnical properties. It is common that in many situations and many places the vegetation action is relegated to a minor contribution in reaching the engineering requisites. Even the search procedures and tests concerning both botanical characteristics and biotechnical properties are not standardized and analytical settled. In this sense a developing model to soil bioengineering must also to propose and to establish analytical procedures and methods regarding the plant species discovery.

In the familiarity issue, the very discipline structuration in an analytical frame and inspiration by a parallelism to the related traditional civil engineering branches lead to an appropriation of the existent familiarity to engineers engaged in traditional techniques. This structuration model also allows, by increasing the rational level at the design and construction procedures, the use of live plant material in infrastructure applications such roadways, railroads, pipelines rights-of-way, energy transmission line corridors, optical cables, etc. Since the aforementioned steps help the development of soil bioengineering as a feasible approach to common engineering applications where careful planning is needed, with live plants to be considered as veritable construction material. In this context, this program contributes to develop the professional institution of soil bioengineering practice, making possible the future creation of practice rules and design codes.

Regarding the promotion and dissemination, the main difficult according Schiechtl & Stern[105] is the remarkable pre-existent reluctance direct to soil bioengineering approach in preference to conventional methods. According to them, this reluctance results from both lack of training and acquired practical experience in such a new field. The analytical developing of soil bioengineering could help or even creates mechanisms to overcome such difficulties. The engineering training modern method is nowadays largely based upon the analytical teaching, which could not be done in the case of an artisan knowledge, whose training depends on years of experienced based apprenticeship.

[105] SCHIECHTL, H. M. & STERN, R. *Handbuch für... Op. cit.*

Final remarks

Soil bioengineering has as its main and distinguishable characteristic the use of live vegetation elements as construction material. Focusing on native species, local natural materials, reduced impacts and modification and the synergy between inert and live materials soil bioengineering techniques are a very suitable approach to stabilize natural systems. This is attained due to the flexibility, nature emulation, and high level of integration exhibited by soil bioengineering schemes.

Soil bioengineering is a branch of civil engineering and has aside its primordial technical functions of stabilize natural systems, further finalities such as aesthetic, ecological and economic objectives. Actually, a soil bioengineering design process embraces more than a typical traditional engineering work, it consists of an ecosystem design.

Although soil bioengineering schemes are not new, the settlement of this discipline as a technical and scientific engineering branch is relatively recent. Soil bioengineering current stage is characterized by an artisan and descriptive approach, commonly exhibited by other engineering disciplines in their gradual developing course. This non-analytical stage of soil bioengineering is characterized by a highly empirical professional practicing, a not fully organized professional institution and a practical experienced-based professional training process.

Many obstacles to soil bioengineering broader acceptance by the engineering community and also difficulties to its developing are a direct consequence of this current descriptive and artisan character. Examples of negative consequences of this present stage are: lack of confidence by designers in the prescription of soil bioengineering measures, irregular and time consuming training processes, long developing processes of new schemes and methods.

As an engineering branch, soil bioengineering could be analytically developed tracing a parallel to its correlated other engineering disciplines. A program to develop and structure soil bioengineering as an analytical engineering field was presented. This program is fundamentally based on a model that clearly interlinks morpho-mechanical botanical characteristics and biotechnical properties of plants to the needed stabilization requisites of natural systems. The proposed program contributes directly to the applicability and the dissemination of soil bioengineering techniques by a broader professional community in a more uniform and rational way. It also allows the use of soil bioengineering schemes in infrastructure applications such as roadway works. This structuration contributes to the developing of new soil bioengineering methods, and to more feasible training processes of such engineering discipline.

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