A QUANTITATIVE APPROACH FOR MEASURING SUSTAINABILITY IN GEOTECHNICAL ENGINEERING

Aditi Misra and Dipanjan Basu*

Department of Civil and Environmental Engineering
University of Connecticut
261 Glenbrook Road, Unit 2037
Storrs, CT, USA.
*E-mail: dbasu@engr.uconn.edu
*Telephone: 1 860 486 5023

Abstract: Civil Engineering is the major instrument of anthropocentric development over centuries through ever expanding infrastructure, cities and facilities. Over the last two decades, a growing awareness is noted towards making such growth sustainable as well. Efforts in setting up standards in construction management are mostly directed towards high level construction and material management but geotechnical engineering that can produce the most permanent change of the land use pattern, lacks proportional attention. Literatures available in this field are found to stress more on qualitative aspects of construction management than on developing quantitative efficiency parameters. This paper studies the energy efficiency of two types of pile foundation, drilled shaft and driven reinforced concrete pile, based on available energy-centric methods like exergy and emergy and provides an aid to the practitioner in making a sustainable choice.

Keywords: *sustainability, emergy, exergy, drilled shaft, driven pile*

1. Introduction

Civil engineering processes (e.g., planning, design and construction of a road network) are both resource and fuel intensive**.** The building industry alone, during the construction stage, uses about 30-40% of the total resources used in the industrialized countries (Pulselli et al. 2003). But this intensive consumption of energy goes unnoticed mainly because of the indirect nature of the energy used in the form of materials and natural resources (e.g., water, wood and land use). Resource efficiency as a decision making metric is slowly gaining momentum in the civil engineering industry, particularly in the construction sector (Jeffris 2008). In fact, sustainable development, which is closely related to efficient resource management, is the current focus of the civil engineering industry and academia. Sustainable development is defined by the Brundtland Commission of the United Nations as 'the development that meets the needs of the present generation without compromising the ability of the future generations to meet their own needs' (Brundtland 1987). Most of the efforts in incorporating sustainability in civil engineering practices are directed towards construction management and material re-engineering (Jeffris 2008).

Geotechnical engineering is most material intensive and produces the most permanent change in the land-use pattern. Consequently, sustainability metrics must be an inherent part of geotechnical planning, design and construction processes. However, a major problem in introducing sustainability in geotechnical engineering is inadequate knowledge of the effect of the processes on the ecological balance of the area (Abreu et al. 2008). There is also an absence of a reference framework which can help in determining the best engineering solution balancing both economy and ecology. These drawbacks are compounded by the scarcity of the geo-sustainability literature in and by the fact that most of the sustainability indicators for geotechnical practices are qualitative in nature (Abreu et al. 2008). Foundation engineering is also plagued by a general reluctance in accepting any other efficiency criterion beside the traditional considerations of cost and technical efficiency (Jefferis 2008).

There is only one set of guidelines available, developed by Jefferson et al. (2007), which couple sustainability with geotechnical practices. It essentially evaluates the effect of a geotechnical construction process on four sectors of efficiency: economic, environmental, social and technical. These broad sectors are then subdivided into subsectors that are of relevance to the project.

The entire system is represented on a circle and a project is marked closer or further from the centre of the circle depending on its achievement level in that subsector. This provides a qualitative guideline at the construction stage of geotechnical projects and is modeled after the general green building codes like BREEAM or LEED. Although these guidelines serve well at the construction stage, there is little or no help available in the decision-making process during the planning and design stages of geotechnical engineering. Considerable energy efficiency can be ensured at the design stage itself with the help of a quantitative framework that considers the energy equivalence of the material and natural resources used in the process.

In this paper, a quantitative sustainability framework is proposed for use with geotechnical engineering, particularly with foundation design. The quantitative framework is based on thermodynamic principles, and two different approaches based on emergy and exergy are used (Odum 1996, Scuibba&Wall 2010). Emergy accounting is an ecocentric method that considers all the work done by nature and man together to make a product. Exergy is the entropy-free energy of a material that can do useful work. The procedure follows a “cradle to grave” approach (McDonough & Braungart,2002) in which the reuse of the materials after decommissioning of the project is not considered. This framework is applied to pile foundations, particularly drilled shafts and driven piles, in order to determine the most environmentally-friendly solution for a few particular sites.

2. Thermodynamic Calculations for Drilled Shafts and Driven Piles

The laws of thermodynamics have been used to develop different sustainability parameters for applications in different processes, e.g., ecological and chemical processes. Both the concepts of emergy and exergy take into account the important fact that, although energy is conserved in any process, its quality is not (Odum 1996, Dincer 2007). This is a particular consequence of the second law of thermodynamics according to which it is impossible to have 100% efficiency for any cyclic process, that is, the generation of a product is always accompanied by an irrecoverable loss of useful energy to its environment. In the following sections a brief overview and calculation methods are discussed for both emergy and exergy and the discussions are followed by applying the particular method for the case study. Since all processes are interlinked it is important to decide a system window consisting of the parts of the process that are of importance. It is necessary for both the methods to have a well defined system boundary across which mass & energy flows. In our case, that boundary is decided to be the physical limit of the construction area. This automatically excludes any environmental effect of transportation to or from the site which is probably not a justified assumption given that distance of construction site from manufacturing unit and landfill site are important considerations in calculating fuel use and emissions from construction related work.

2.1 Emergy Based Calculations

Emergy, spelled with an ‘m’, measures both the work of nature and that of human beings in generating services and products. While energy is a measure of the amount of work that can be obtained from a product, emergy is the available energy already used up to make that product (Odum1996). Products for economic use are made from both renewable and non renewable natural resources and services. The resources can be local to the production process or brought in from outside. Emergy of all the inputs, resources and services are added up to arrive at the emergy of the product. However, the quality of energy content of one resource is not the same as that of another and they have different work capacities. Hence, for the purpose of comparison, it is necessary to have a common basis to which all other forms can be converted. Commonly, solar energy is used for the purpose. The available solar energy used up directly or indirectly to make a service or product is defined as solar emergy and its unit is solar emjoules (sej). Different energy forms are converted to equivalent solar emergy by a transformation coefficient, also known as transformity, which is defined as the solar emergy required directly or indirectly to produce 1J of a product or service. The solar emergy U of a product coming from a process is given by:

$$U = \sum_i \left[(Tr)_i \, E_i \right] \qquad i = 1,\ 2,\ \ldots,\ n \tag{1}$$

where E_i is the available energy content of the i^{th} independent input material/energy flow to the process and $(Tr)_i$ is the solar transformity of the i^{th} input material/energy flow and n is the total number of material/energy flows.

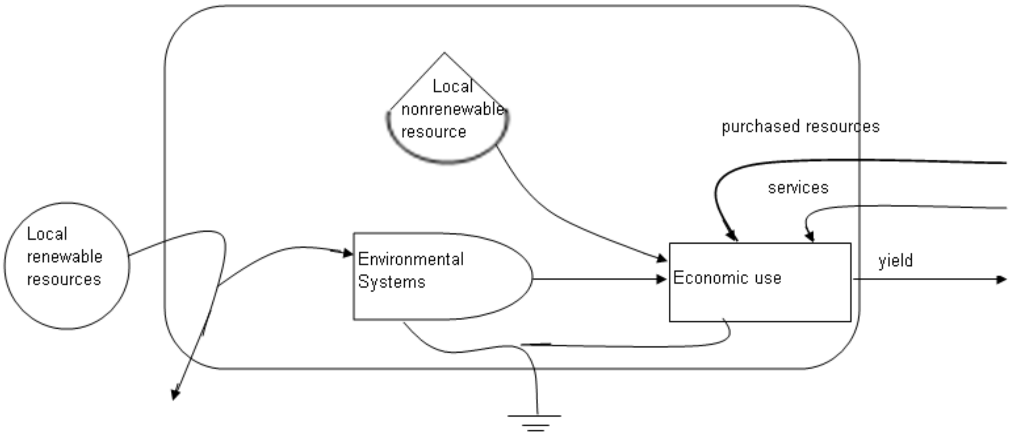

Figure 1. *Diagram illustrating the production process by emergy flow diagram (from Ulgiati and Brown 1997).*

2.2 Emergy calculation for driven and drilled piles:

A comparative analysis of the requirement of the natural resources and materials for two common type of pile foundations, drilled shafts and, reinforced concrete driven piles are made in this paper. This is a hypothetical problem of a single pile required to carry a structural load of 10000KN. The pile is embedded in a homogeneous sand deposit with a relative density of 60%. The water table is assumed to be at the ground surface and the pile length is 12m The piles are embedded in a fully submerged sandy soil with relative density of 60%. From the above data, the diameter of the driven pile is calculated to be 1.5m and that of the drilled shaft to be 2.5m. The corresponding volumes of land use, concrete and steel are also calculated for each case. The following tables detail the emergy calculation for this case study.

TABLE 1: *EMERGY Calculation for Drilled Shaft Foundation*

Item	Specification	Volume m3	Density Kg/m3	Raw Data	Unit	Transformity sej/unit	Reference:	Emergy Sej
Solar Irradiation	NOTE 1							
Land Use NOTE 2	Soil Erosion (Soil organic matter =3%)	9.62	20.31×10^4	$19.53\times10^5 \times0.03 = 0.59\times10^5$	Kg	$5.4 \times 4186 \times1.24\times10^5 = 2.8\times10^9$	Odum (2000)	1.65×10^{14}
	Soil Excavation (Soil Organic matter =1%)	105.83	20.31×10^4	$214.9\times10^5 \times 0.01 =2.14\times10^5$	Kg	$5.4\times4186\times1.24\times10^5 = 2.8\times10^9$		5.99×10^{14}
Concrete NOTE 3	Pile	58.9	2500	1.47×10^5	Kg	1.54×10^{12}	Brown & Buranakaran (2003)	2.26×10^{17}
Steel	As pile reinforcement	35.3	7850	2.77×10^5	Kg	4.13×10^{12}	Brown & Buranakaran (2003)	11.44×10^{17}
	As in Construction machinery	NOTE 4						
Fuel	For Electricity generator	NOTE 5						
	For machinery operation							
Total Emergy driving the process of drilled shaft construction is 13.7×10^{17} sej (based only on soil, concrete and steel used)								

TABLE 2: *EMERGY Calculation for Driven Pile*

Item	Specification	Volume m3	Density Kg/m3	Raw Data	Unit	Transformity sej/unit	Reference:	Emergy Sej
Solar Irradiation	NOTE 1							
Land Use NOTE 2	Soil Erosion (Soil organic matter =3%)	4.9	20.31×10^4	$9.97\times10^5 \times0.03 = 0.3\times10^5$	Kg	$5.4 \times 4186 \times 1.24\times10^5 = 2.8\times10^9$	Odum(1996)	0.814×10^{14}
	Soil Excavation (Soil Organic matter =1%)	0	20.31×10^4	0	Kg	$5.4 \times 4186 \times 1.24\times10^5 = 2.8\times10^9$		0
Concrete NOTE 3	Pile	21.2	2500	1.47×10^5	Kg	1.54×10^{12}	Brown & Buranakaran (2003)	0.816×10^{17}
Steel	As pile reinforcement	12.72	7850	0.9985×10^5	Kg	4.13×10^{12}	Brown & Buranakaran (2003)	4.12×10^{17}
	As in Construction machinery	NOTE 4						
Fuel	For Electricity generator	NOTE 5						
	For machinery operation							
Water	Water expelled during compaction	21.2	1000	0.21×10^5	Kg	1.95×10^9	Pulselli et al. (2007)	0.14×10^{14}
Total Emergy driving the process of driven pile construction is 4.95×10^{17} sej (based only on soil, concrete and steel used)								

Notes to the Tables:

NOTE 1: Solar irradiance is calculated as the solar energy received by the construction area during the construction period (Pulselli et al., 2007) In this hypothetical case study the difference is negligible as we consider single pile areas but in reality the number of piles required in a foundation depends on pile capacity. As can be deduced from the calculation, driven piles have a higher capacity than drilled piles and hence the foundation area required might substantially differ in large scale construction projects.

NOTE 2: It is assumed that top 1m soil suffers erosion due to any construction activity and its organic matter content is about 3% decreasing to 1% at depths greater than that (Pulselli et al., 2007). For driven pile, only the top 1m is affected by construction while for drilled shaft the entire volume of soil mass needs to be excavated to put the shaft in place. Removal of soil mass removes with it soil nutrients that are essential for thriving of bacterial colonies. Not much study is available correlating these two factors but commonly it can be concluded that the lesser a system is forced to deviate from its original state, the more sustainable it is.

NOTE 3: Cement industry accounts for 30-40% of CO_2 emissions to the environment. As construction debris also, cement is mainly responsible for clogging drainage systems in the locality. Cement particles suspended in air is a predominant health hazard. It is only evident that a foundation option that uses lesser quantity of cement is more acceptable than one that uses more of it.

NOTE 4: Steel used in machinery is calculated as percentage present by weight in the machinery. Multiplied by transformity it gives the emergy in that account (Pulselli et al., 2007).The inclusion of steel in machinery as an input is not always obvious particularly when system boundary does not include the machine manufacturing unit. This is typical of emergy analysis which provides a holistic approach including every form of energy that is required for the process to take place. Since machinery is an integral part of construction process, it is assumed that energy that went into making the machinery also goes to the making of the pile.

NOTE 5: Fuel efficiency is important both for environmental and economic resource. Fuel use varies widely depending on machine type and process. Spaulding et al.(2008) has shown that the CO_2 emission increases 1450 times only on the basis of fuel usage if a traditional ground improvement technique is used instead of dynamic compaction .
For this particular case study, literature from DELMAG about equipments show that the fuel usage of excavators is 25-30l/hr while that for diesel hammer for pile driving(of length 11-60m) is only about 7.5l/hr.

2.3 Remarks:

The calculations made so far leads us to conclude that driven pile is a more sustainable choice than drilled shafts. However, use of drilled pile is limited by the site condition- dense or rocky strata may be uneconomical and even technically unfeasible for driven pile. In such cases, alternative ways to make the construction process sustainable can be thought of like using bio diesel instead of fossil fuel, replacing non renewable materials by bio-engineered materials and such other newer approaches to make the built environment eco-friendly.

Since foundation is an almost permanent structure, it is considered as storage of the emergy inflow in the process of its construction. Emergy in the output flow should be calculated at the stage of dismantling of the structure. This study gives the partial picture and can be used as a decision making tool when the energy input is the major concern without any consideration for reuse of the materials. Thus, for a cradle to cradle approach, the emergy of reusable/recyclable materials obtained after decommissioning should also be considered to arrive at the net emergy used in the process.

3.0 EXERGY and EXERGY Analysis Applied to Drilled Shaft and Driven Pile

3.1 EXERGY

Exergy is defined as the amount of work that a system can perform when it is brought into thermodynamic equilibrium with its environment. In terms of energy, exergy is the available or entropy free energy of a system. However, unlike energy, exergy is not conserved and depends on the state of the reference environment.

Exergy of a homogeneous system at a defined state 1 is given by:
ex1=ex1,t+ex1,c+ex1,k+ex1,p+ex1,n+ ….

Where ex1,t ex1,c ex1,k ex1,p and ex1,n are the thermodynamic, chemical, kinetic, potential and nuclear exergy components of the total exergy . (Sciubba &Wall 2010)

Parameters have been developed over years to quantify efficiency of processes on the basis of exergy Dewulf et al.(2000) defined 'Renewability Parameter' as (exergy consumption of renewable resources)/(total exergy consumption) and 'Efficiency parameter' as (exergy value of the useful products)/(exergy consumed in the process + exergy required for the abatement of the harmful emissions). Lems et al. (2003) defined exergy efficiency as the useful exergy flow out/ exergy flow into the process (Hau et al. 2004)

Mathematically, exergy is commonly represented per unit mass as

$$\mathbf{B = \Delta[H - T_0S + \Sigma x_i\mu_i + v^2/2 + gz]}$$

where H = enthalpy
T_0 = temperature of the reference environment
S=entropy
x_i=mole fraction of component i
μ_i =chemical exergy of the component i
v=velocity
z=height

And Δ is the difference w.r.t temperature, pressure and the composition between current and reference state

As is evident from the definition, exergy analysis requires the definition of a reference state that should remain constant throughout the calculation. The environmental reference state commonly used is 1atm and 25C and composition of the air, oceans, and a selected thickness of the earth's crust. Standard chemical exergy values are available from literature (Szargut et al.1988).

3.2 Exergy Analysis of Drilled and Driven Pile:

Cumulative exergy consumption (CExC) developed by Szargut (1988) calculates the total exergy consumed in the making of a product. For our particular case study, we will use the CExC method to determine efficiency of the two types of foundation on the basis of consumption. As seen in emergy analysis, in this case also, to arrive at the net exegy consumption, we need to know the state of materials at the dismantling stage and their exergies. Then, net exergy consumption = cumulative exergy consumption – exergy of the residual materials.

For the inflow only, exergy being additive, we can have:

Cumulative exergy flowing into the process of construction (CExC) = Exergy of Cement + Exergy of Steel + Exergy of Fuel.

Berthiume & Buchard(1999) has calculated exergy of cement concrete for dry process to be 5.35 MJ/Kg and for wet process to be 10.2 MJ/Kg. The exergy of steel is 41MJ/Kg with the assumption that steel is fully oxidized at the end of its useful life (Szargut 1988). Exergy of diesel fuel is 42.7 MJ/kg (Dincer & Rosen 2007)

Since this is a hypothetical case study, the exergy due to actual fuel use cannot be determined but the high exergy content of diesel fuel indicates that use of heavy machinery that consumes large amount of fuel will end up with higher CExC.

From calculations shown in Table 1 &2, both the mass of cement concrete and steel used in construction are higher for drilled shaft than driven pile. Hence, the cumulative exergy consumption will also be higher for drilled shaft than driven pile.

3.3 Remarks

Exergy analysis includes the raw materials used in process but it fails to account for the energy contribution of the natural resources that are in their natural (standard) state (Berthiume & Buchard ,1999). For example, in our case, exergy of soil excavated for the purpose of construction does not make any contribution to the process exergy until it undergoes a chemical property change when disposed in landfill as soil is considered to be in its standard state in the lithosphere. Similarly, the emission of CO_2 in cement manufacturing process does not affect the exergy of cement until a significant change in noticed in the standard atmospheric conditions.

4. Conclusion

Major anthropogenic changes of the environment are due to indiscriminate use of natural resources for technical advancement. We as engineers are the main sculptors of this technology oriented society and it should be a primary concern for us to rethink and re-evaluate existing systems so that the future generation does not have to compromise on their requirement for our contribution to this system. Towards this goal, civil engineers have a greater responsibility as they provide the basic infrastructure of social development. Geotechnology as the foundation of any civil engineering construction and also as an interface between nature as soil and the built environment has an immense potential to economize the use of the resources and energy if properly managed.

Foundation construction is a large and complex process engineering that involves exploitation of natural capital in the form of land and water use, human labor and material use. It is clearly evident that indiscriminate use of any of these is going to affect the ecosystem adversely in both short and long term. However, this industry is still focused on technological and economic efficiency and absence of proper study into a possible contradiction between technical efficiency and energy efficiency has led to a lack of general consciousness. Both drilled shaft and driven pile are two most commonly and traditionally used pile foundation whose usage till date has been singularly dictated by market economics and technical considerations. Being engineers, we admit that technical feasibility is of paramount importance in all projects but energy considerations can bring a third dimension in decision making when alternative choice is technically not limiting.

As methods, emergy analysis seems to better represent the energy consumption in geotechnical processes. Emergy provides an ecocentric economic valuation of ecosystem goods and services and is considered by many as a more holistic approach to environmentally conscious decision making. The methods of LCA or exergy analysis are more focused on emissions and their impacts and fail to capture the critical nature of contribution of ecosystems to human well being (Hau & Bakshi 2004). This paper provides a quantitative reference framework based on both the methods of energy utilization to help the future practitioners in this field take a more informed decision that will promote sustainable growth.

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