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Interconnected Street Networks Result in Mixed-Use: A Key to Alleviating Auto Traffic
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Interconnected Street Networks Result in Mixed-Use: A Key to Alleviating Auto Traffic

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Abstract

After World War II, mass automobile production brought mass production of highways and low-density residential in far-flung suburbs of US cities. This resulted in trip origins far from destinations, causing traffic congestion, air pollution, and energy consumption at a high cost. Two scenarios were modeled: interconnected and hierarchical street networks. The former can accommodate mixed-use effectively, and the latter cannot. The result revealed significantly lower auto traffic, vehicle miles, and hours of travel in the grided roadway network. Reducing traffic is synonymous with making origins close to destinations which is made possible by grided roadways and mixed-use.

Keywords: interconnected roadway; grid; hierarchical roadway; mixed-use; connectivity; walkability

1. Introduction

Roadway networks are the framework upon which cities are built. Once urban streets are designed and constructed, their pattern determines how cities will form and function in terms of traffic congestion, environmental quality, and energy consumption. Moreover, roadway networks and, consequently, urban form affect the lifestyle of people, their level of activities, how they socialize, and even their health and wellness [1]. Therefore, a city cannot apply best practice features most effectively unless its roadway framework as its foundation is done right. A conventional roadway network based on the sparse hierarchical functional classification to include cul-de-sac, local, collector, arterial, and expressway roads is meant for the mobility of autos. Such roadway networks funnel most of the traffic in a few major wide roads and junctions and lack connectedness to make the cities walkable; therefore, it is the manifestation of an automobile-dependent system (e.g., suburbs in the US cities), whereas a highly interconnected grid roadway network, whether regular, irregular or winding with small city blocks, with all roads having a fairly similar function (e.g., European cities or downtowns in the US cities), evenly distribute traffic, is a pedestrian-friendly system and can also accommodate other modes of transportation including bicycles and public transit the best way possible through more direct routes. A good example of an inter-connected roadway network is the Central Business District (CBD) of Portland, Oregon, which is grided with small blocks size and is very well connected with mixed land use. On the other hand, an example of a hierarchical roadway is Ashland, a low-density residential suburb of Boston, Massachusetts. Low-density residential suburbs are less permeable and cannot be served by frequent public transit service in the best way possible due to a lack of connectedness and being less walkable. Moreover, such roadways cannot support the density required to make public transit work efficiently and cost-effectively. Examples of these two types of roadway networks are shown in “Fig. 1.”

Fig. 1. Interconnected grid street network, CBD Portland, Oregon (top), hierarchical roadway network, Ashland, Suburb of Boston, Massachusetts (bottom)

The roadway network acts as a foundation of the city fabric and has been the most permanent feature of the cities, with a high resistance to change throughout history [2]. This is also because the land use juxtapose follows and is formed according to roadway layout and resists any change. The historical grid network of US downtowns and many bends and curbs and narrow roads of the cities in Europe supports mixed land use and have stayed the same for many years regardless of any changes in technology or the economy. Low-density suburbs support isolated land use types far from each other following the roadway hierarchy. For example, commercial use agglomerates around expressway interchanges, whereas single-family residential uses are away and built in the local streets and cul-de-sacs. Cities will continue to function mainly based on their roadway foundation as the key determinant. Hence, smart cities require smart foundations. Disruptive technologies, including connected and autonomous vehicles (CAV), electric vehicles (EV), Mobility as a Service (MAAS), or Intelligent Transportation System (ITS) features, will not be the panacea. Technology is an enabler and catalyst. It will amplify the current system. If a city is auto-oriented and has a sparse hierarchical roadway network, technology can increase its roadway capacity to accommodate even more automobiles; on the other hand, if a city is grided, walkable, and transit-oriented, technology can enhance that even further. In brief, before building back cities smarter with technology, those car-centric urban areas must retrofit their roadway pattern to fix the foundation first.

2. What Did Not Start Smart? Historical View

Traffic is defined as the movement of different modes of transportation along a route between origin and destination pairs. Using such a definition, common sense is that reducing traffic is possible by bringing origins closer to destinations. In other words, working at home has the origin and the destination at the same location so that traffic will be eliminated. When origins are close to destinations (mixed use), cities have less traffic. When origins are far from destinations (suburbs), cities have more traffic. The mass production of automobiles led to the mass production of highways in US cities after World War II. The extensive highways then became the main framework that shaped cities by building mass production of low-density houses known as "cookie cutter houses" in the far-flung suburbs. This resulted in US cities becoming auto-oriented and brought more traffic plus air pollution, energy consumption, and high capital and maintenance cost. In the recent decade, technology has been wrongfully generalized as the solution to relieving traffic congestion. The same hype existed when automobiles were introduced, and highways and wide roads were considered the ideal solution for transportation.

After World War II, from 1950 to 1970, trip origins were extensively separated by trip destinations far away and connected by miles of highways. This became the main reason for generating traffic. 1.2 million houses, mainly single-family dwelling units, were constructed in the suburbs yearly. The housing inventory increased by 50%, or 21 million units [3]. In 1970 more people lived in far suburbs than in the cities [4]. Since 1970, the number of cars and trucks in the United States has grown twice that of the population. As a result, vehicle miles traveled (VMT) increased by 41%, even though the population grew by only 4% [5]. In the US, a federal policy supported funding and investing in highways. The Federal-Aid Highway Act of 1956 called for the construction of a 41,000-mile Interstate Highway System, which was to be completed by 1970 at approximately $27 billion. The system's design called for connecting large urban areas and connecting highways to central cities [6]. These highways with limited access and low connectivity peaked just a decade before travel demand per person reached the maximum in the United States in 2005 [7]. This means sprawl was closely correlated with more traffic, and highways also adversely impacted the environment and energy consumption [8].

The result has been what Peter Calthorpe (2018) [9] calls the "villain" of an urbanizing planet – referring to sprawl which segregated people by economic and land-use enclaves and discouraged the cross-fertilization and interaction among people that enables society to thrive. Extensive highways destroyed divided neighborhoods, primarily black and poor, disrupted pedestrian movements, communities lost their public spaces, and small businesses were significantly hurt. The concept of community was diminished as a result, and the outcome has been traffic congestion, space consumption, energy waste, environmental pollution, traffic accidents, adverse health consequences, and car expenses. In the last century, significant spending on transportation systems has been billions of dollars funneled into highway construction [10]. Moreover, the government at all levels has cut transit system revenues (and thus transit service). The destruction of public transit and making American cities auto-dependent has been to the extent that in the 1950s, many of the rail transit vehicles were destroyed and were dumped in junk yards, as shown in "Fig. 2." [11].

Fig. 1. Pacific Electric cars are piled up awaiting destruction at Terminal Island, 1956. Source for Image (Wikipedia): https://en.wikipedia.org/wiki/Pacific_Electric#/media/File:Junked_streetcars.jpg

While highways and wide roads were considered the solution to urban problems, there was also some resistance to those plans. Such differences are reflected in the plans developed for New York State by Robert Moses, considered among the most influential post-World War II urban planners who oversaw all public work projects in New York. His influence on federal highway policy extended well beyond New York. His idea was to build cities for automobiles and not for people, and he said, "go right through cities and not around them" [12]. In contrast was the position taken by the activist Jane Jacobs who organized grassroots efforts to protect neighborhoods from "slum clearance" — in particular, Moses' plans to overhaul Jacobs' own Greenwich Village neighborhood [13]. Moses' plan for the Lower Manhattan Expressway would have destroyed the neighborhoods of Soho and Little Italy, and Jacobs was instrumental in the project's eventual cancellation. These neighborhoods experienced a renaissance in subsequent years. Jacobs' book, The Death and Life of Great American Cities [14], was a powerful rebuttal to Moses' mode of thinking, and her actions provided a convincing argument against his mode of operating [15]. Such contrasts could also arise with the disruptive technologies which have become very popular in the last decade. Technology per se should not be synonymous with "smart." If the substance of any action is smart, automation will make the system smarter. Furthermore, the main requirement for smart substance is the underlying street framework of the cities. The roadway network functions as the framework and is a self-reinforcement force. However, if the overall framework is inefficient, automation will exacerbate the inefficiencies [16].

3. Interconnected Street versus Hierarchical Network – The Framework

Generally, as described in the introduction earlier, there are two types of street networks. One which focuses on connectivity and is grided, whether regular or irregular, in the forms of uniform rectangles, radial, informal web, or a wrapped grid. The other type is hierarchical roadways, also known as dendritic or tree-like, which at its lower level has dead-end cul-de-sacs and higher include freeways with minimal access [17]. These two types are also referred to as Traditional Neighborhood Development (TND) versus Conventional Suburban Development (CSD). The most effective grid network requires small city blocks size.

Economies of scale refer to those goods and services where the average costs per unit of output decrease with the increase in the scale. This is also related to scale efficiency, meaning each service unit may become more efficient with the increase in scale. Studies find that roadways have deficiencies of scale. The legendary smart growth engineer Walter Kulash (2011) [18] compares Traditional Neighborhood Development (TND) with Conventional Suburban Development (CSD) and states that "streets become less (not more) efficient as their size increases. So instead of an efficiency of scale as the street gets larger, we experience deficiencies of scale instead". This implies that, for example, four two-lane roads function with a higher level of service than an eight-lane road, although they both have the same number of lanes. The reason is that the TND street pattern with dense interconnected and smaller roads provides more choices to turn, and traffic will be distributed more evenly among alternative routes. Each junction takes a smaller turn volume, whereas the CSD roads impose many travelers to funnel into a few wide roads causing bottlenecks at the intersections. This is shown in "Fig. 3." presenting both types of street patterns; each has eight traffic lanes.

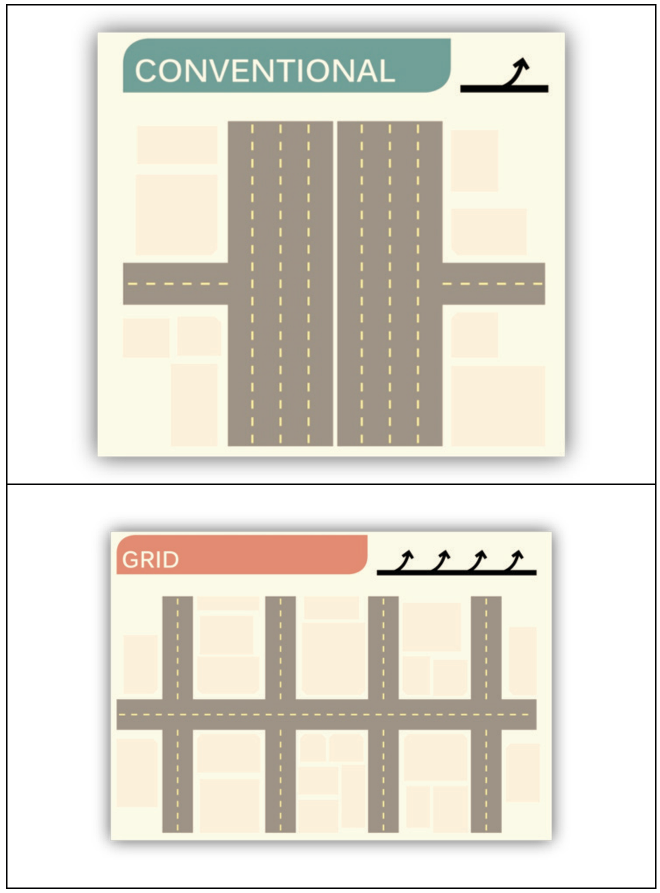

Fig. 3. Hierarchical Roadway (top) funnels a large volume of autos in a few intersections, causing bottlenecks. In contrast, the grid network (bottom) distributes traffic evenly and provides more choices from every origin-destination pair.

Moreover, TND street patterns are more pedestrian-friendly and transit-oriented, free up more space and have greater people-moving capacity. Furthermore, the land use in the TND street pattern is mixed; hence origins are close to destinations, whereas naturally, in hierarchical roadways, commercial uses are formed around interchanges, and residentials in the local streets are farther out.

Like how different types of automobiles have different chassis, a sedan car cannot be used on a truck's chassis or a sports car and vice versa; a sparse hierarchical roadway framework is auto-dependent. It cannot accommodate features like mixed land use, public transit, and pedestrian-friendly places in an effective way. On the contrary, once cities have interconnected street networks as their framework, other elements considered as best practice urban and transportation planning, such as multi-modal transportation, mixed land use, and even technology, can be fitted the best with such a framework.

4. Materials and Methods

To evaluate the performance of the two roadway network patterns, including the grid and hierarchical, TransCAD, a GIS-capable transportation planning software, was used to model the two systems [19]. The part of the roadway network that forms the Central Business District (CBD) of Portland, Oregon, as shown in "Fig. 4." was used as the base. Then the divided highways in this network were removed. Roadways were all coded as either one or two-lane streets in each direction to represent a full grid roadway network, as shown in "Fig. 5." The same base network was also significantly modified to replicate the hierarchical roadway to include the expressway at its highest level and cul-de-sac at its lowest level of roadway functional classification as shown in the same figure.

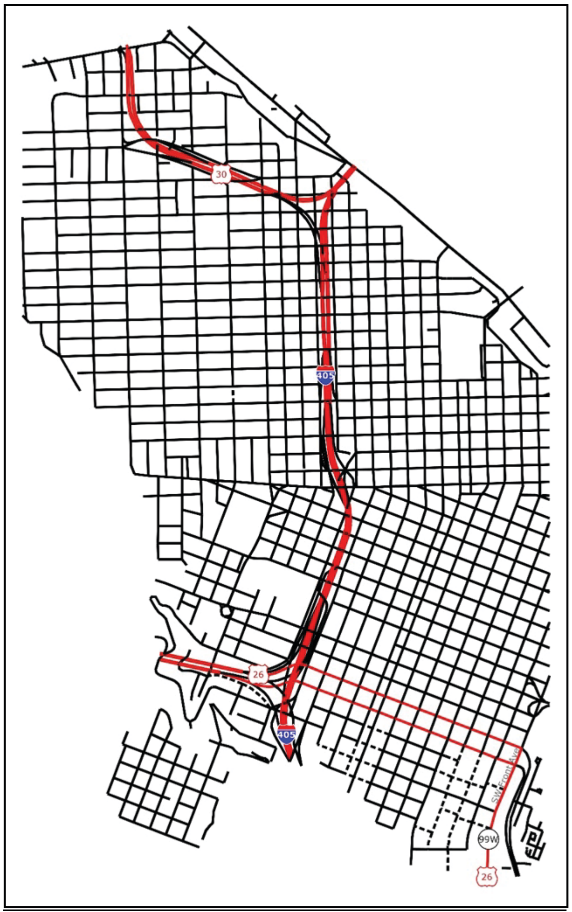

Fig. 4. Hierarchical Roadway (top) funnels large volume of autos in a few intersections, causing bottlenecks. In contrast, the grid network (bottom) distributes traffic evenly and provides more choices from every origin-destination pair.

The models developed in this study are hypothetical, and the assumptions are based merely on the objective of evaluating two different roadway networks with the total capacity of the two systems being the same. Then the same auto travel demand was assigned to these two roadway networks to evaluate the performance of each grid and hierarchical roadway. The assumptions made for the two roadway networks are presented in Table 1 and Table 2 for the grid and hierarchical roadway networks, respectively.

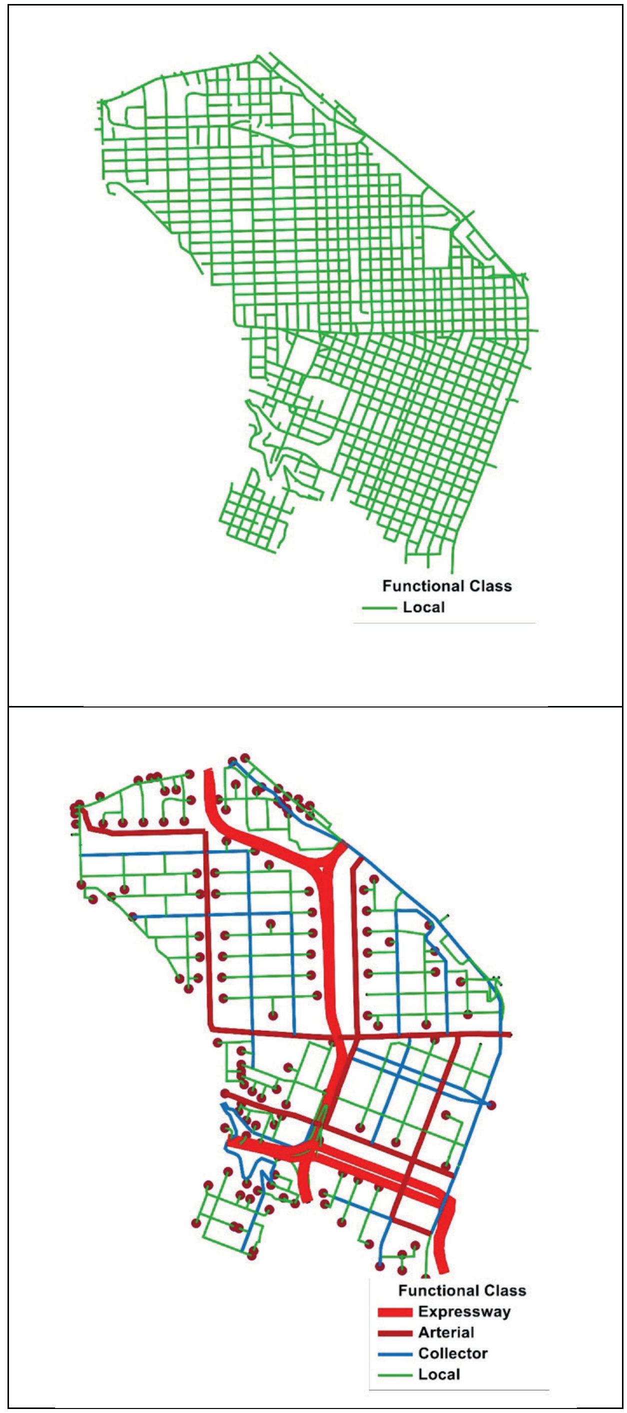

Fig. 5. Portland CBD base roadway modified to replicate full grid (top), also modified to replicate hierarchical roadway network (bottom)

Table 1: Lane miles and total roadway capacity, grid roadway network

Type	Lane Length (Lane Miles)						Roadway Capacity	
	1 Lane One-Way	1 X 1 Lanes	2 X 2 Lanes	3 X 3 Lanes	4 X 4 Divided	Total	Per Lane	Total Vehicle Capacity Miles
Street		109.5	158.3			267.8	700	187,490
Total		109.5	158.4			267.9		187,490

Table 2: Lane miles and total roadway capacity, hierarchical roadway network

Type	Lane Length (Lane Miles)						Roadway Capacity	
	1 Lane One-Way	1 X 1 Lanes	2 X 2 Lanes	3 X 3 Lanes	4 X 4 Divided	Total	Per Lane	Total Vehicle Capacity Miles
Local/Ramp	1.6	48.9				50.5	700	35,350
Collector		2.7	41.1			43.8	900	39,420
Arterial				39.6		39.6	1,200	47,520
Expressway				8.7	23.9	32.6	2,000	65,200
Total	1.6	51.6	41.2	48.3	23.9	166.6		187,490

The demand side was estimated using a hypothetical simplistic (sketch) model. The assumptions were not as crucial for this evaluation as long as the total demand and the roadway capacity were the same for both the grid and the hierarchical roadway networks. The demand side of the travel demand forecast model includes the following components.

1. Transportation Analysis Zones (TAZ) – The TAZs were developed as similar hexagons covering the roadway network. Hexagons were delineated based on a quarter of a mile radius (five-minute walking distance). The total area of all TAZs is 4.11 square miles.
2. Number of residents was assumed at 76,365, which results in 18,580 residents per square mile (the same as San Francisco) considering the total area of TAZs. Assuming one breadwinner for every three residents, 25,455 jobs were assumed. Considering that in a hierarchical roadway network, employment centers are usually agglomerated around expressways, and residential uses are at the outskirts, but in a grid network, employments centers and residential uses can be mixed, the distribution of these attributes is assumed, as shown in “Fig. 6.”
3. Auto trips entering for one hour PM peak for a typical weekday were assumed as *0.48*jobs plus 0.0012*residents*. Auto trips exiting for one hour PM peak for a typical weekday were assumed as *0.34*jobs plus 0.0017*residents*. These assumptions were based on the Institute of Trip Generation (ITE) trip generation rates for retail (weighted based on 10%), office (weighted based on 90%), and apartment, and unit of measurement were converted to residents and employment based on assumed population employment density.
4. External trips were assumed to be 30,000 auto trips for entering and exiting the site.
5. Auto trips were balanced and distributed based on the following function.

   $$Tij = Exp(-Lij/30)$$

   Where,

   Tij is auto trips at one hour PM peak between each origin (*i*) destination Pair (*j*).

   L is the Euclidean distance between each origin (*i*) destination pair (*j*).

6. The one-hour PM peak trip table, which includes a total of 29,510 auto trips for both the grid and the hierarchical roadway networks but with different trip distribution patterns, was then assigned on each of the grid and hierarchical roadway networks using the Bureau of Public Roads (BPR) Volume Delay Function (VDF) to estimate auto traffic volume on links, and level of service on each system.

5. Results and Discussion

The same hypothetical one-hour PM peak demand of 29,510 auto trips was assigned on the grid and hierarchical roadway network with the same vehicle miles capacity of 187,490. The result based on the volume-to-capacity (*V/C*) ratios on links were calculated as depicted in **“Fig. 7.”** showing that the hierarchical roadway network has many links where volume exceeds the capacity and causes traffic congestion on the roadways. The congested links on the hierarchical network are overutilized, whereas many links are underutilized. The auto trips on the grid roadway network are evenly distributed and therefore make the grid roadway network more efficient.

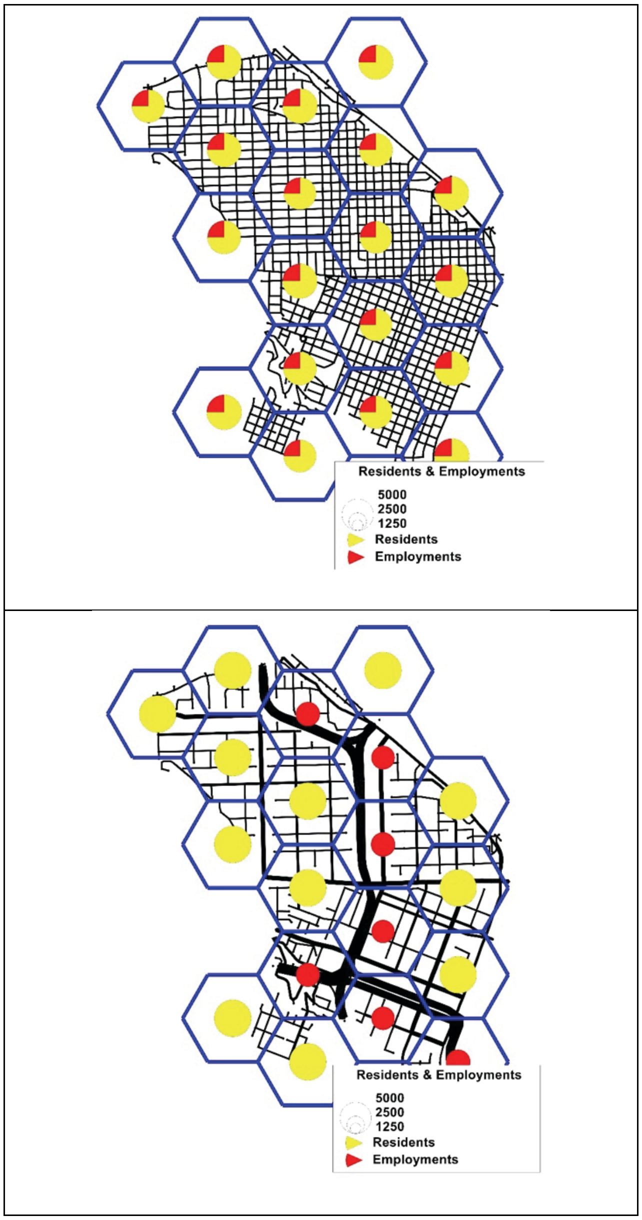

Fig. 6. Residents and employment distribution on grid roadway network as mixed use (top), and on hierarchical roadway network (bottom) by hexagons transportation analysis zones (TAZ)

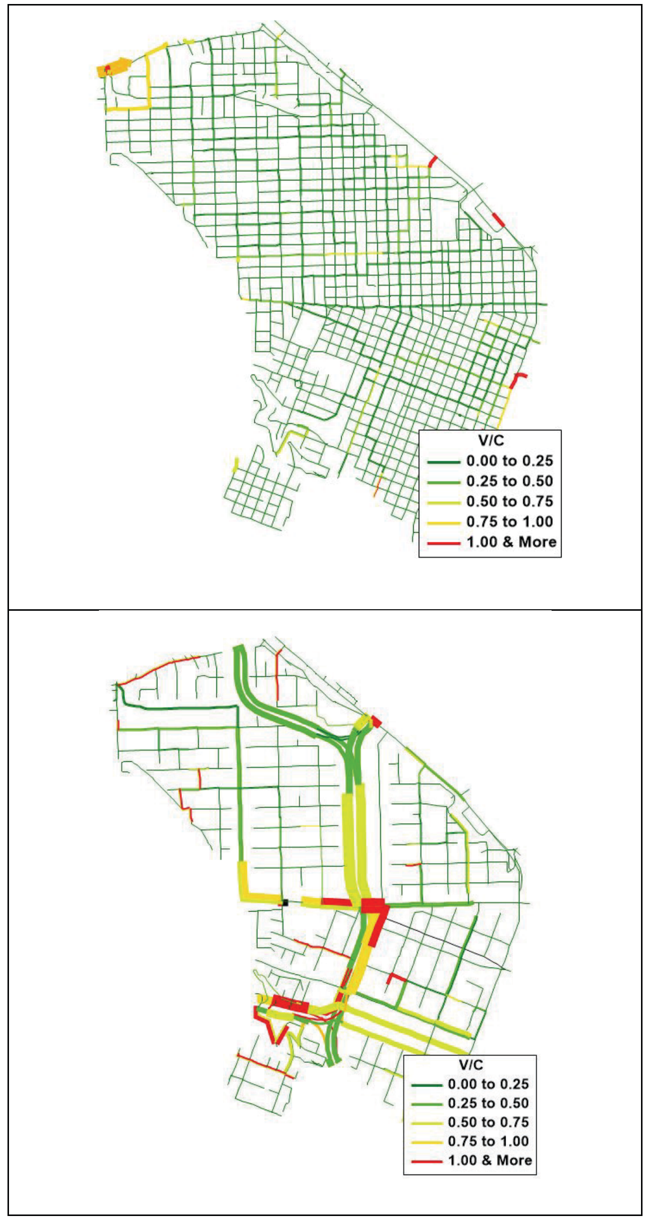

Fig. 7. Link volume to capacity Ratio (*V/C*) on grid roadway network (top), on hierarchical roadway network (bottom). Red colors Highlight the congested Links.

Moreover, the following Measurements of Effectiveness (MOE) were also estimated by each roadway network pattern to evaluate the performance of each system, as presented in Table 3.

1. Vehicle Miles of Travel (VMT) - A measure of all the miles driven by autos on links at one hour PM peak.
2. Vehicle Hours of Travel (VHT) - A measure of the hours driven by autos on links at a one-hour PM peak.
3. Average Speed (Miles per Hour) – This is the average speed weighted by all the autos and calculated based on VMT divided by VHT.
4. VMT Congested – This indicator measures VMT only on links where the volume-to-capacity (*V/C*) ratios are above one. This is an indicator to represent the level of traffic congestion.
5. VHT Congested - This indicator measures VHT only on links where volume-to-capacity (*V/C*) ratios are above one. This is also another indicator to represent the level of traffic congestion.

The result indicates that in hierarchical roadway networks, travelers are imposed to go out of their way – due to the disconnected network – to reach their destination, causing vehicle miles of travel (VMT) and vehicle hours of travel (VHT) to become significantly higher and resulting in traffic congestion. Furthermore, the grid roadway network not only provides direct and, therefore, shorter routes between the origin-destination pairs but also, due to mixed land use in the grid roadway network, which can naturally be formed ubiquitously along the roadways, the distance between origins and destinations are lower. While the average speed is lower in the grid roadway network because each roadway is narrower and the average per lane capacity is less, however, due to the interconnectedness of the roadways and mix of land use, the overall trip length represented by VMT and trip time represented by VHT, as well as traffic congestion becomes significantly lower. The evaluation conducted in this study is conservative because the overall area is only 4.11 square miles. In reality, cities are much larger in area size. Therefore the residential land uses are located much farther in far-flung suburbs following the expressways in the hierarchical roadway network causing VMT and VHT to become much more. Furthermore, the grid roadway network, due to having direct routes and also mixed land use, results in short trips and therefore leads to much higher walking trips and public transit trips compared to the hierarchical roadway system. These effects are not assumed in the modeling analysis conducted in this paper.

The direct routes between origin-destination pairs represent the level of connectivity and are measured by the following Measurement of Effectiveness (MOE) using TransCAD software (Caliper, 2021).

Sinuosity: Ratio of route distance to straight-line distance.

Gamma Index: Ratio of the number of links in the network to the maximum possible number of links between nodes. Values are 0 to 1, e.g., 0.54 means the network is 54 percent connected.

Alpha Index: Ratio of the number of actual circuits to the maximum number. Values range from 0 to 1, with higher values representing a more connected network. Values <0 & > one possible (if the network is not a true circuit.)

The walkability measure is represented by the following criterion.

Weighted Intersection Density: Weights are applied to intersections based on valency (the number of links connecting at the node). For walking, for example, conventional 4-way intersections on regular streets would be more attractive to walking (weight = 1). In contrast, 3-way intersections (weight = 0.5) or intersections with a major highway (weight = 0) would discourage walking, and cul-de-sacs and dead-ends (weight = 0) would be a direct barrier to walking.

Table 4 presents the connectivity and walkability measures by the grid and the hierarchy of roadway networks.

Table 4: Measurement of effectiveness (MOEs) representing traffic condition by grid versus hierarchical roadway network

Measurement of Effectiveness (MOE)	**Hierarchy Roadway Network**	**Grid Roadway Network**
Total Auto Trips at One Hour PM Peak	29,510	29,510
Total Length Weighted by Capacity	187,490	187,490
Vehicle Miles of Travel (VMT)	56,633	9,827
Vehicle Hours of Travel (VHT)	1,535	547
Average Speed (Mile per Hour)	37	18
VMT Congested	11,562	1,800
VHT Congested	612	216

Table 4: Measurement of effectiveness (MOEs) representing connectivity and walkability by grid versus hierarchical roadway network

Connectivity & Walkability Criteria	Hierarchy Roadway Network	Grid Roadway Network	Description
Sinuosity	1.04	1.01	Values start from 1, with lower values representing more direct routes.
Gamma Index	0.43	0.58	Values range from 0 to 1, with higher values representing a more connected network.
Alpha Index	0.14	0.37	Values range from 0 to 1, with higher values representing a more connected network.
Intersection Density	180	816	Higher values represent a higher level of walkability.

6. Conclusion

This study briefly reviewed the history, indicating how the mass production of automobiles brought the mass production of highways in US cities. As a result, land use segregation led to low-density residential sprawl far from activity centers. Streets lost their characters and became merely conduits to move automobiles which ultimately even defeated the intended purpose. The roadway system, which has highways as its spine, forms a hierarchical network that is tree-like, and the branches are not interconnected. Therefore, travelers have fewer route choices and are imposed to make out-of-direction traffic to satisfy their trips. Such roadway networks funnel most of the traffic into a few wide roads defeating their purpose and causing highways and wide roads to become congested again. The disconnected roadway and segregated land use result in a high level of vehicle miles and hours of travel. Moreover, long trips and indirect routes in the low-density suburbs discourage the use of non-motorized transportation as well as the use of public transit. Considering the definition of traffic as moving on a route between a given origin to a destination, the remedy to reduce traffic is only by bringing origins close to destinations. Once an origin is located at the same place as a destination, there will be no traffic, such as when people work from home; when origins are close to destinations, that means creating mixed land use where residential, commercial, retail, etc. can coexist together in a compact setting causing less auto traffic. On the contrary, a hierarchical network and highways have substantial flaws since, by default, it separates land uses. Hence, any mitigation will not be effective unless origins become closer to destinations which, in effect, means creating a different roadway network based on a grid system, whether regular or irregular, in a compact setting.

Conversely, an interconnected roadway network based on the grid system, whether regular or irregular, with small city blocks provides travelers with multiple route choices. It evenly distributes traffic with reasonable volume to the roadway network with narrower streets. The pattern of the roadway network, which does not follow a hierarchical system, does not discriminate in using the streets. Therefore, all streets can accommodate all different land uses mixed vertically and horizontally, making origins close to destinations and, therefore, less traffic. All these attributes, including the directness and short routes, also encourage non-motorized transportation. The compact and high-density development that is resulted from the interconnected network also increases the use of public transit. “Fig. 8.” and “Fig. 9.” illustrates how these two different frameworks of roadway network bring different outcomes and results.

The simplistic travel demand forecast model developed in this study using TransCAD software evaluated two scenarios, including an interconnected roadway network based on grids and small blocks and a hierarchical roadway network. The capacity length and total trips were the same in both scenarios. The difference was mainly the roadway pattern. The same magnitude of population and employment was also coded in both models but with different distributions. The grided network applied mixed-use, and in the hierarchical network, population and employment were segregated. The result clearly showed that the hierarchical network has more traffic, higher levels of congestion, higher vehicle miles of travel, and higher vehicle hours of travel. Moreover, performance measures were calculated to evaluate the connectivity and walkability of each scenario, indicating that the grid network has a higher level of connectivity and therefore is more walkable. The result of the travel demand forecast models is conservative since the scenarios are replicated in a small subarea. The hierarchical network will function even worse since it will force residents to move farther from their employment. Moreover, the grid network shifts part of travelers to non-motorized and public transit, which is not considered in this modeling exercise.

This research can be further elaborated by using actual data at a regional scale. Comparative analysis between two existing regions, one using a hierarchical roadway network and one with a grid network, and studies on retrofit and infill strategies to convert the suburban sprawl and hierarchical roadway network to compact places with interconnected roadway networks are among the areas which require more research and will be very beneficial.

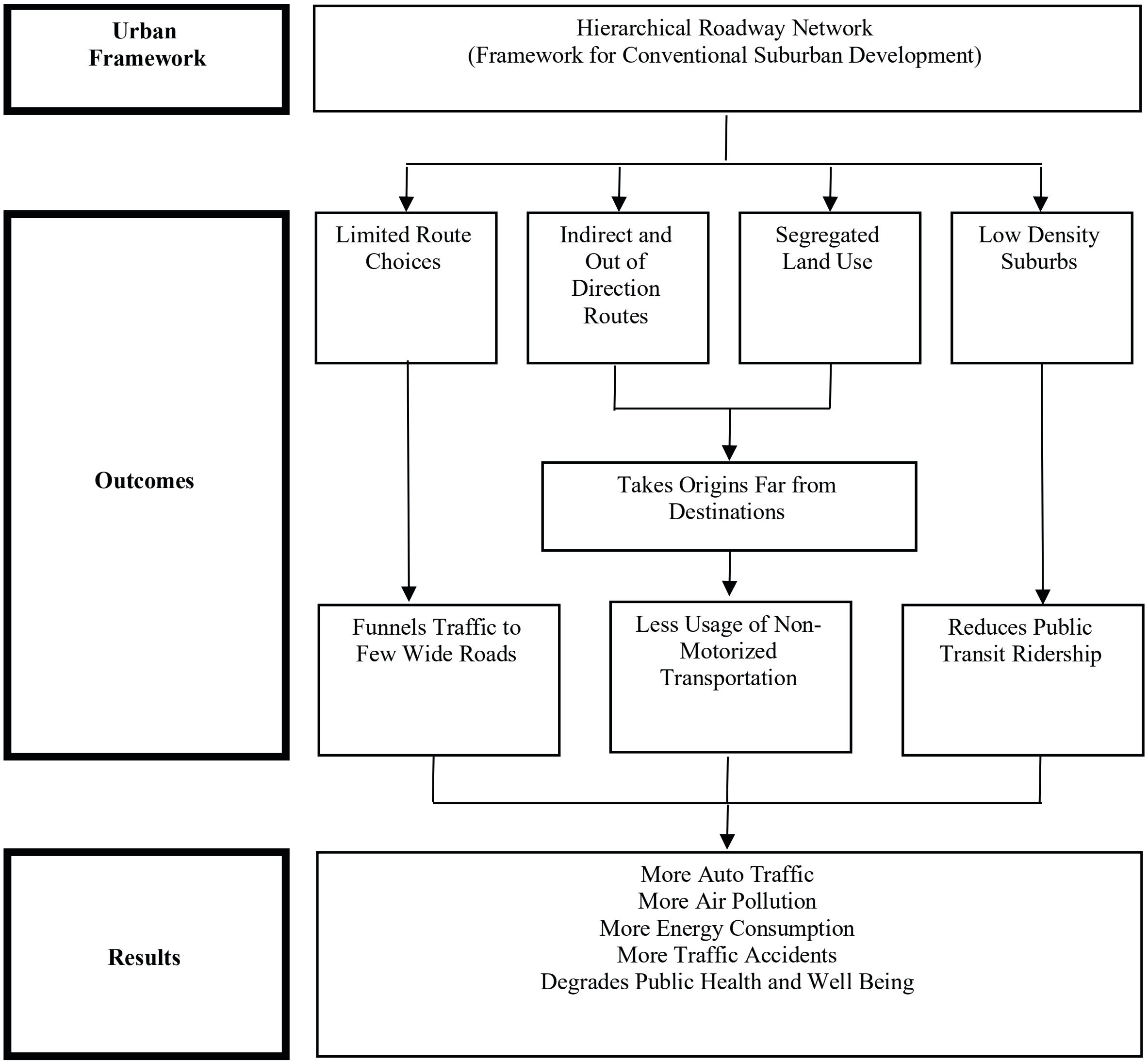

Fig. 8. Hierarchical roadway network, outcomes, and results

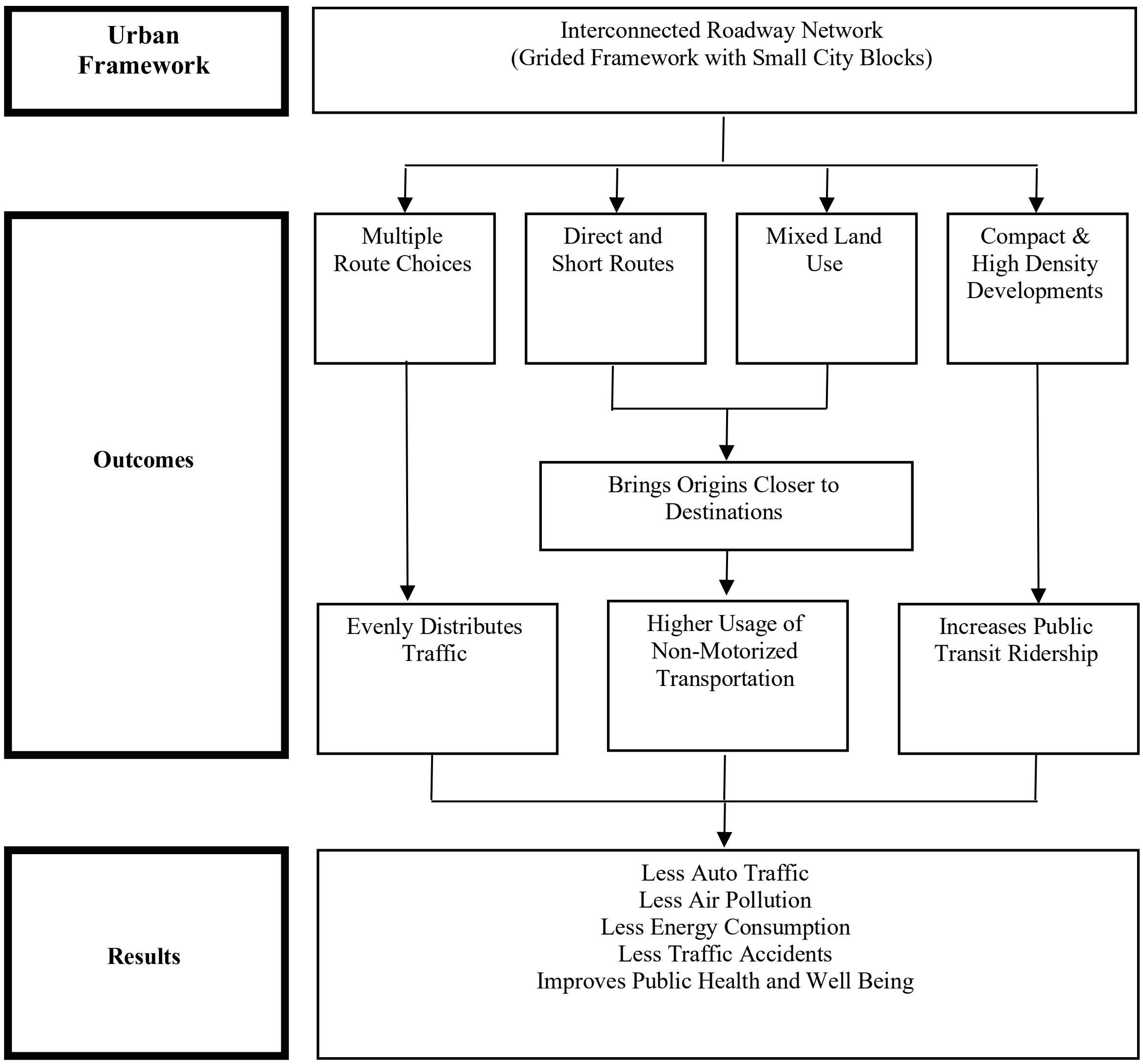

Fig. 9. Interconnected roadway network, outcomes, and results

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Abstract

Geotechnical projects generally consume large quantities of resources and energy and release considerable amounts of CO_2 in the atmosphere, and therefore, have a significant impact on the environment. To minimize this effect, sustainable solutions and materials have been proposed and adopted in the literature and practice as alternatives to conventional methods wherever applicable. This study reviews and discusses sustainability in geotechnical engineering, in particular, three ground improvement techniques including deep soil mixing (DSM), dynamic compaction, and vibro replacement (VR) compared to the piling method. Some eco-friendly recommendations are proposed to mitigate the environmental loads of the discussed ground improvement techniques. Moreover, carbon footprints of three case study projects, each with three alternative solutions (i.e., piling, DSM, and VR), are assessed and compared in two conditions, namely, with and without eco-friendly measures (i.e., substituting new materials with recycled or recovered construction materials or with the by-products of other industries). In the studied cases, the CO_2 discharge amounts of DSM and VR were found to be around half and one-tenth of that amount in piling. The CO_2 emissions of all three products showed a significant decrease when adopting the eco-measures, averagely, 34, 60, and 14% for piling, DSM, and VR, respectively. Finally, the CO_2 emissions of the above cases are presented in functional units.

Keywords: Carbon Footprint, Sustainability, Piling, Deep soil mixing (DSM), Vibro replacement (VR), Ground Improvement.

1. Introduction

Construction industry devours a large portion of raw materials taken from the Earth's crust, namely, sand, gravel, and stones, and approximately 40% of the globally consumed energy (Dixit et al., 2010). Moreover, sizable construction projects can potentially contribute to desertification and deforestation, as well as land, water, and air pollutions (Kibert, 2008; Basu et al., 2015). Earthworks and geotechnical phases of civil projects are no exceptions and can more directly affect environmental components (e.g., groundwater, shorelines, bays, and the like) due to their nature. Hence, improving geotechnical processes while considering more environmentally friendly aspects will help in achieving a more sustainable society.

In construction projects including geotechnical phases, financial aspects have been typically considered as the main, if not the only, design and performance criteria in the past decades (Basu and Puppala, 2015). Accordingly, reducing the CO_2 footprint of geotechnical activities has gained the attention of geotechnical researchers in past years (Fragaszy et al., 2011). More recently and thanks to increasing awareness regarding sustainable developments and constructions, the trend is turning to take the overall cost and environmental impacts as the two key factors of the decision process of projects (Shillaber et al., 2016a). The term "Carbon Critical Design" refers to designs in which carbon emission is considered as a critical parameter (Clarke, 2010).

When it comes to ground and foundation engineering, ground improvement techniques are usually known to be less harmful to the environment compared to conventional solutions such as deep or heavy foundations in terms of CO_2 emission and energy consumption, subject to the type of technology, design and other project specific factors (Spaulding et al., 2008; Egan and Slocombe, 2010; Gomes Correia et al., 2016).

In this study, first, sustainability in geotechnical engineering is discussed, and then three ground improvement techniques (i.e., vibro replacement, dynamic compaction, and deep soil mixing) are described together with some recommendations to minimize their environmental loads. The introduced assessment approaches and tools in the literature and practice are briefly reviewed as well. Next, the environmental impacts of three real projects, for which various alternative geotechnical solutions were proposed, are analyzed and discussed, and finally, the eco-friendly recommended measures are applied to the studied cases to evaluate their influences. The results of this work, however, should not be generalized to other geotechnical projects unless detailed studies have been carried out.

2. Sustainability in geotechnical engineering

Pachauri et al. (2014) reported that human-sourced CO_2 emissions have continuously increased since the late 19th century. Chang et al. (2019) provided an overview regarding the effect of climate events on geotechnical hazards and a statistical review of the correlation between the occurrence of and damage from, geotechnical hazards (e.g., landslides, ground subsidence, levee failures, soil degradation, and coastal erosion) and greenhouse gases (GHG) based on historic disaster data. They concluded that there has been a clear link between the amount of GHGs in the atmosphere (CO_2 concentrations in particular) and the onset of climate changes and geotechnical hazards during 1900 – 2017 (Fig. 1). The atmospheric concentration of CO_2 has raised from 280 to 400 ppm during 1750 – 2015 (Pachauri et al., 2014; Dlugokencky and Tans, 2019). Consequently, the global mean temperature is continuously growing which clearly alters the mean sea level among other damages (van Aalst, 2006; Chang et al., 2019).

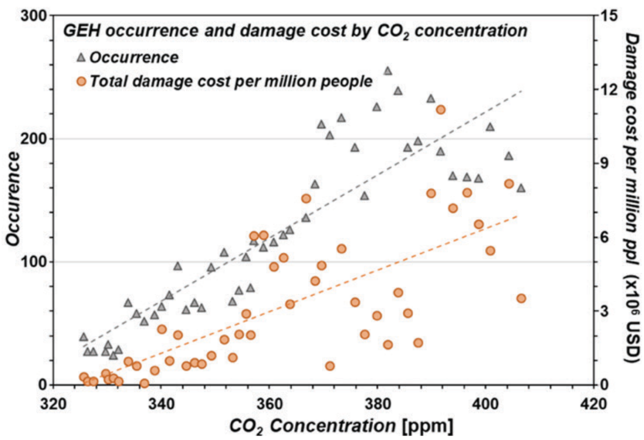

Fig. 1. Occurrence of geotechnical hazards vs. CO_2 concentration in the air (Chang et al. 2019)

According to Parkin (2000) and Pearce et al. (2012), a process is sustainable if it continues without exhausting the resources or damaging the ecosystem. Sustainability in civil engineering (including geotechnical works) can be improved by reducing energy and natural resource consumption and GHG emissions while increasing the life span of the project and implementing more eco-effective methods. In the geotechnical fields, the focus should be put on utilizing natural resources as less as possible and optimizing the design in a way that less mobilized materials and equipment are needed and high energy-intensive products are minimized or substituted with more energy-efficient materials resulting in less adverse impacts on sustainability. In addition, other areas of focus were using recycled or recyclable materials, reducing solid waste, water, and air pollutions, and taking all environmental considerations before altering the land use pattern, for example, in land reclamations, landfills, and shoreline or massive excavation/backfilling projects (partially from Fragaszy et al., 2011; Gomes Correia et al., 2016; Chang et al., 2016).

Regarding ground engineering projects, Chittori et al. (2012) proposed that geotechnical engineers should devise some ground improvement alternative solutions, carry out extensive analyses on the carbon footprint, life cycle costs, and energy consumption for each method, and eventually, determine the one that is proven to be the most sustainable. Of course, technical feasibility and more importantly client's interests shall also be considered in making final decisions regarding economic issues.

2. 1. Assessment of environmental impacts

Life cycle assessment (LCA) provides a quantitative analysis for identifying the environmental impacts of a product, procedure, or project over its entire life cycle (cradle-to-grave) or only from the extraction of resources until the construction phase (cradle-to-gate) subject to study boundaries (the International Organization for Standardization, 2006). The CO_2 emission or the embodied CO_2 (ECD) is considered as an important part of LCA. ECD is defined as the amount of CO_2 emitted during manufacturing and handling a particular product (e.g., cement or aggregate productions, transportation, and storage) or a process (e.g., ground improvement, piling, or any other construction activity). Furthermore, ECD can be linked to, but not synonymous with, other sustainability metrics such as embodied energy and waste production (Egan and Slocombe, 2010).

GHGs absorb infrared radiation from the Earth's surface and prevent its escape into outer space (The United States Environmental Protection Agency, 2012). Schneider (1989) and Rodhe (1990) estimated that the GHG absorbs approximately 20% of the radiant heat. Among GHGs, CO_2 is the most widely studied gas since the quantity of the released CO_2 is significantly higher compared to other gases. Usually the amount of CO_2 generated from a specific product or process is considered as an indication of the total GHG emissions. The environmental impacts of all GHGs are converted to that of CO_2 and presented as CO_2-eq (carbon dioxide equivalent). In the LCA of a hypothetical project, Inui et al. (2011) concluded that the quantities of non- CO_2 GHG emissions (e.g., CH_4 and N_2O) were negligible compared to the amount of CO_2 released in the air in the same process; although, contribution of the GHG components depends on the studied process.

To develop a streamlined approach for evaluating the environmental impacts of the ground improvement techniques, Shillaber et al. (2016a) argued that the emissions of CO_2 alone can be considered in carbon footprint analyses instead of CO_2-eq in geotechnical engineering. This eliminates the difficulties in quantifying various non-CO_2 GHGs contributing to the CO_2-eq. Moreover, it is better to use CO_2 instead of the energy consumption of a project since the continued growth of renewable energies (e.g., wind, solar, tidal, geothermal, or hydroelectric) can lead to less CO_2 emissions but energy consumption (partially green) could remain high (Shillaber et al., 2016a).

2. 2. Assessment tools

Several databases are introduced in the literature guidelines or standards for the LCA parameters (e.g., GHG or CO_2 emission, embodied energy, produced waste, global warming potential, and the like) of a wide array of products and processes which cover the base materials and the prerequisite steps of the concerned product or process. It is worth noting that each item contributing to the selected LCA parameter(s), including GHG or CO_2 emission factors, should be identified and addressed for assessing the overall environmental impact of a project. Next, their involvement should be quantified with respect to the records or estimations of the project and the indicated factors in a selected database. The most important items in geotechnical engineering are cement, steel, aggregate, fuel, transportation, equipment manufacturing and depreciation, manpower supply and welfare facilities, ready-mixed concrete, and waste disposal. Subject to the type of projects, usually, construction materials (e.g., cement and

steel) are the largest contributors to GHG emission and energy consumption in civil construction projects (Shillaber et al., 2016a; Inui et al., 2011 and Vukotic et al., 2010).
Shillaber et al. (2016b) presented a method called "streamlined energy and emission assessment model" (SEEAM) to compute the energy consumption and CO_2 emissions of ground improvement projects. Misra and Basu (2011) proposed an LCA procedure including environmental impact assessment as a quantitative assessment tool to incorporate sustainability in geotechnical engineering. Likewise, Hammond and Jones (2011) provided a comprehensive database for the carbon and energy impacts of construction materials. The UK Environment Agency (www.environment-agency.gov.uk) developed a carbon footprint calculator. Similarly, Holt et al. (2009) and later Holt (2011) designed a program named "GeoSPeAR", which is a tool in which the multi-dimensional sustainability performance of a geotechnical project is indicatively and qualitatively illustrated based on social, economic, environmental, and natural resources and twenty sub-criteria. Global Emission Model for Integrated Systems (GEMIS) is another programme developed based on the database provided by the Institute for Applied Ecology, Technical University Darmstadt, Germany. Goedkoop et al. (2008) and later Huijbregts et al. (2016, 2020) introduced and corrected a tool named "ReCiPe", which is the life cycle impact assessment method incorporated in SimaPro 8.0.2 software (PRé Consultants B.V., 2010).

Mainly for piling and ground improvement applications, the Deep Foundations Institute (DFI) in partnership with the European Federation of Foundation Contractors (EFFC) released a methodology for analyzing equivalent carbon footprint (CO_2-eq) in geotechnical projects, together with an excel spreadsheet incorporating their methodology, assumptions, and database (Lemaignan and Wilmotte, 2013).

Many other carbon calculators or LCA tools exist in the literature or the market (e.g., Prism LCA Calculator, Keller Carbon Calculator, Cementation Skanska Carbon Calculator, Green Siesta Carbon Calculator, and the like).

3. Ground improvement techniques

In this section, three ground improvement techniques potentially overlapping with piling applications (and employed in the case studies of Section 5) are introduced with their benefits, challenges, and areas of application, namely, vibro replacement (VR), dynamic compaction (DC), and deep soil mixing (DSM).

3. 1. Vibro replacement (VR)

VR, also known as the vibro stone column technique, is one of the most widely implemented ground improvement solutions, consisting of the installation of pile shape elements made of aggregates into the natural subsoil for enhancing the bearing capacity of the ground, decreasing the settlement, and mitigating liquefaction susceptibility. Two main technologies exist for installing stone columns, including top- and bottom-feed methods, which are also referred to as wet or dry methods, respectively.

In the top-feed method, a vibrator suspended from a crane is penetrated into the ground with the electric-powered vibration and high-pressure water jet. The soil surrounding the vibrator and its extension tube liquefies creates a cavity and lets the aggregate fed on the ground surface sink and create the stone column. In the bottom-feed method, the vibrator is penetrated down to the design depth in the same way as in the top-feed method. Then, the aggregates are fed into a funnel and transported down to the tip of the vibrator through a channel. During the withdrawal steps, aggregates run from the vibrator tip into the created annular space and form the stone column (Kirsch and Kirsch, 2010).

VR could be highly challenging and difficult to execute in extremely soft soils where the in situ soil is unable to provide enough lateral support to hold the stone column in its shape. The unnecessary overconsumption of the aggregate and accordingly heave in the surrounding areas are expected in such grounds.
Limited spoil and thus less material wastage are generated in the bottom-feed method. In both bottom and top-feed methods, some measures can be implemented to avoid excessive aggregate consumption as follows:

- Installing trial stone columns based on pre-fixed parameters, recording the consumption and the diameter of columns and comparing it with the required nominal diameter;
- Assessing the pre-fixed production scheme as per the trial outcomes (i.e., the electrical current of the vibrator, surging intervals, and corresponding stone consumption);
- Revisiting the installation procedure (i.e., establishing a current, surging intervals, and stone volume per column that meets design objectives);
- Proposing as per site condition measures to be undertaken to recycle effluent stones from the surface or around the depo area by screening the material;
- Performing trial columns as per design and subsequent load tests in accordance with the project specification, and if possible, optimizing the design.

Serridge (2005) presented some applications of recycled and secondary aggregates for vibro stone columns. Recycled aggregates are mainly construction and demolition arisings (crushed concrete and brick) and spent a railway ballast and secondary aggregates are typically the by-products of other industrial processes (not previously used in construction) such as metallurgical slags, waste rock, and foundry sand. Serridge concluded that such alternative aggregates are of significant benefit through:

- Reducing demand on natural aggregate resources and the associated environmental impact (disturbance and transport);
- Decreasing the disposal of materials to landfills.

Similarly, Raymond et al. (2017) found that using recycled materials in VR can significantly reduce environmental impacts by generating 45% less GHG. On the other hand, the distance of the quarry has a great influence on the CO_2 emission of VR. The overall carbon footprint is twice as much if the transportation distance increases from ~10 to ~70 miles, which is in line with the findings of Serridge (2005) and Jefferson et al. (2010). Locally available aggregates (even quarried) might be more beneficial compared to recycled but transported ones since it is unsustainable to transport alternative materials to long distances if natural aggregates are available considerably closer to the construction site. It should be noted that transportation has a large portion in the CO_2 emission of VR projects. In this regard, recycling opportunities may need to be evaluated on a case-by-case basis. However, Zöhrer et al. (2011) noted that recycled aggregates may not be consistently energy- and CO_2-efficient, but leave less disturbance to nature compared to quarried aggregates.

3. 2. Dynamic compaction (DC)

DC is a ground improvement technique that densifies soils by releasing a 10-to-30-ton pounder (rarely heavier) from a height of normally 5 – 30 m. The ground is subjected to repeated surface tamping in a uniform grid of compaction points called "prints". No imported material is needed in typical DC, therefore, it is considered as an environmentally friendly solution and recommended wherever applicable. Conversely, this technique is time consuming or inapplicable for soils containing more than 25 – 30% fine content. Another limitation of this technique is the influence depth, which hardly goes beyond 10 – 12 m. Nonetheless, DC is widely implemented for the uniform and general treatment of loose sands or newly backfilled grounds (Kirsch and Bell, 2013). The load-bearing capacity of DC-treated grounds is typically less than that of other ground improvement techniques and thus DC alone is not considered as an alternative to piling although a combination of DC and VR can lead to significant design optimization.

Given that no foreign material is needed in DC, the only way to minimize its CO_2 emission would be by optimizing the energy consumption by:

- Avoiding drops that only displace the soil and cause heave instead of compacting the ground;
- Avoiding compaction more than a project demand (over-compaction).

A comprehensive trial campaign is recommended to assess the most favorable compaction scheme with respect to the soil condition and project needs in which the drops are split into several passes (drops on the same print but after some resting times) and phases (drops on new prints in between the existing prints). Moreover, various print spacings should also be tested to reach the widest grid which complies with the project specification.

3. 3. Deep soil mixing (DSM)

DSM comprises mixing a binder (typically Portland cement type I) with in situ soils to increase the bearing capacity of the ground. In the so-called wet DSM procedure, the binder is fed into the ground in the form of slurry through hydraulic pumps and hoses, injected at the tip of the drilling shaft and thoroughly mixed with the soil in several surging cycles. The mixing is performed with discontinuous augers of 0.8 – 1.2 m (in diameter) attached to the drilling shaft (Kirsch and Bell, 2013; Topolnicki, 2015, 2016).

Although DSM is less environmentally harmful than conventional piling systems, it is not an eco-friendly technique compared to other ground improvement methods (Shillaber et al., 2016b; Zöhrer et al., 2010; Raymond et al., 2017), which is due to its cement consumption. Thanks to numerous advantages in terms of strength, durability, and economic aspects, cement still dominates the construction market among other construction materials. On the other hand, its sustainability and long-term impacts have become the major concerns of researchers and engineers in the field of civil and environmental engineering over time. The process of cement production emits CO_2 in two ways, namely, the kiln calcination ($CaCO_3 \rightarrow CaO + CO_2$) and the combustion of fuels (i.e., coal, oil, or gas) for heating. On average, one ton of cement would generate nearly one ton of CO_2 (Andrew, 2018).

In soft clays or organic soils, depending on the project requirements, DSM is probably not a cost-, time-, and ecologically-efficient product as an excessive amount of binder (cement) is needed. Another environmental challenge of DSM is hard strata in the subsoil profile. In order to pass through hard layers with the drilling shaft, a huge amount of cementitious slurry should be pumped much more than the estimated quantity required to achieve the design strength.

To reduce the impacts of DSM on the environment, alternative binders should be added to or totally replace the ordinary Portland cement (OPC). One of the recommended alternatives is Ground Granulated Blast-furnace Slag (GGBS), which is a pozzolanic material and a by-product of the steel manufacturing process. Raymond et al. (2017) found that the CO_2 emission can be reduced by 42% if 50% of the Portland cement is substituted by the slag binder. In addition, Zöhrer et al. (2010) showed that DSM columns with GGBS can produce ~30% less carbon footprint compared to similar columns including Portland cement. Likewise, Soleimani Fard et al. (2020) analyzed the technical characteristics of DSM materials made with 100% Portland cement and with 30% Portland cement plus 70% GGBS. All observations were repeated for two different levels of binder inclusion for each binder type. Their results proved that the substitution of cement with GGBS increased the unconfined compressive strength of DSM samples by 15 – 30% and significantly improved the electrical resistivity (as an indicator for the durability of materials) of the tested DSM mixtures by 16 – 19 times (all after 60 days of curing).

4. Like-for-like studies

Zohrer et al. (2010) compared energy consumption and CO_2-eq emission of ground improvement techniques (i.e., VR, DSM, and vibro-mortar and vibro-concrete columns), as well as CFA (continuous flight auger) and bored piles per linear meter of elements using GEMIS software. However, to provide a more realistic comparison of the solutions on a like-for-like basis, they presented the carbon footprint in the form of CO_2-eq per total carried load of each technique (ton CO_2-eq/kN) for a hypothetical project (a 100×200-m-large raft foundation under 50 kPa load). Using GEMIS software, v. Wintzingerode et al. (2011) compared the CO_2-eq emission of bored piles and the VR of a real project in units of ton per carried load and per loaded area. The CO_2-eq was 2.68 ton/MN and 0.27 ton/m2 for bored piles while 0.23 ton/MN and 0.02 ton/m2 for VR.

Egan and Slocombe (2010) studied the environmental impacts of VR and DC methods in comparison with CFA and driven cast in situ piles for six different projects and found that ground improvement methods can offer sustainability advantages using a like-for-like comparison, and thus concluded that ground improvement alternatives (i.e., VR and DC) typically yield a saving of around 90% in carbon emissions. They used various sources for the CO_2 emission factors of their construction materials (e.g., Hammond and Jones, 2008; UK Environment Agency, 2009).

Shillaber et al. (2016b) presented a case study of a levee construction to illustrate the use of the SEEAM model. For this purpose, three design alternatives including DSM, prefabricated vertical drains (PVD), and a reinforced concrete T-wall were compared to determine embodied energy and CO_2 emissions. DSM was not more eco-friendly than PVD, nevertheless, it was eventually proposed for the studied project since it could technically and operationally satisfy project requirements. The total CO_2 of PVD, DSM, and T-wall was 64,000, 147,000, and 211,000 tons.

Raymond et al. (2017) analyzed and compared the environmental and economic impacts of five ground improvement methods (i.e., VR, DC, DSM, vibro compaction, and earthquake drain) performed in a hypothetical project of 50×50-m ground treated to the depth of 10 m. The resources and emissions of each ground improvement method were calculated over the entire life cycle from raw material extractions through the end of construction operations. They concluded that the CO_2-eq of DSM is extremely higher than the other studied techniques, making it unfavorable as a geotechnical solution. The carbon emission of DSM was around 1,700 tons while it was below 100 tons for other techniques. However, the applicability of the techniques should have been studied to have a better like-for-like comparison. Unlike mass mixing technologies, DSM columns are typically not used for uniform treatments of an area, but only under the footprint of foundations where higher levels of loads are concentrated.

5. Case studies

In this paper, the CO_2-eq emission of three different geotechnical projects are estimated as per the EFFC-DFI (European Federation of Foundation Engineering and Deep Foundation Institute) analyzing methodology and database incorporated in an excel-based tool named EFFC-DFI Carbon Calculator (version 4). This tool is developed specifically for deep foundations and ground improvement activities, featured with requirements and parameters of a wide range of ground engineering products, and is compatible with GHG Protocol Product Life Cycle Accounting and Reporting Standard, Bilan Carbone (of France), PAS 2050, and ISO 14067. In this tool there are four different sources for carbon emission: Bilan Carbone, US EPA (United State Environmental Protection Agency), UK DEFRA (Department for Environment, Food and Rural Affairs), and EFFC-DFI recommended values which is used in this study. The databases are open; and in case region/country specific data are available, the user can modify the emission values.

The projects are selected in different scales and designs although all with pilling, DSM, and VR alternatives. The case studies are presented in Table 1. The designs and operational details of the projects are beyond the scope of this research, but alternative options were studied and designed to satisfy project requirements. Therefore, a realistic like-for-like comparison can be concluded from these projects.

In case A, first, the ground is treated by DC in order to optimize the VR solution, followed by executing stone columns. In the CO_2-eq assessment of this case, emissions associated with the DC work are also taken into calculations.

Table 1: Details of the studied cases

		Unit	Case A	Case B	Case C
Location			Oman	Egypt	UAE
Foundation type			Storage tank	Storage tank	Residential
Foundation area		[m^2]	9,855	2,043	820
Ground pressure		[kPa]	250	278	90
Working shift			Day/night	Day/night	Day
Piling	Diameter	[m]	1.2	1.0	1.0
	Number of piles		428	172	24
	Depth	[m]	30	30	15
	Production sets		1	1	1
	Mobilization distance	[km]	2,000	300	60
	Costs (estimated)	[UDS]	3,149,000	984,000	75,000
DSM	Diameter	[m]	1.0	1.0	0.9
	Columns' pattern	[m]	2.3×2.3	2.2×2.2	3.5×3.5
	Depth	[m]	16	14	8
	Production sets		2	1	1
	Mobilization distance	[km]	2,000	300	60
	Costs (estimated)	[USD]	2,843,000	460,000	82,000
VR	Diameter	[m]	1.0	1.0	0.8
	Columns' pattern	[m]	1.7×1.7	1.5×1.5	2.5×2.5
	Depth	[m]	18.5	20	8
	Production sets		2	1	1
	Mobilization distance	[km]	2,000	300	60
	Costs (estimated)	[USD]	1,976,000	544,000	31,000

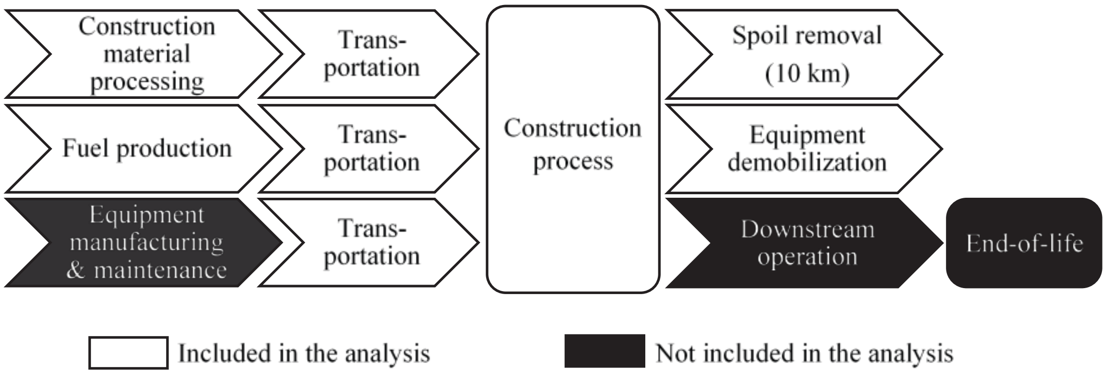

Fig. 2. Simplified process map and items included in or excluded from the calculations of this study

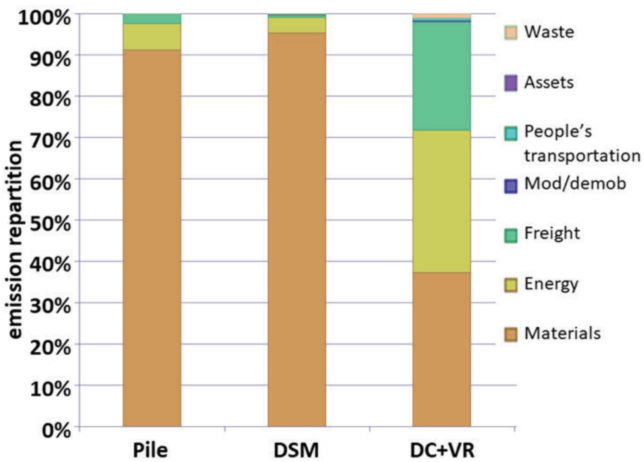

Fig. 3. Contribution of different constituents in the CO_2-eq emission of case A

Several items were within the boundaries of analyses, containing construction materials including normal wastage (aggregate, cement, potable water, concrete, and steel rebars), diesel and petrol, transportation of equipment from the workshop to the site and vice versa, accommodation and transportation of manpower, and waste transportation up to 10 km. However, some other items, which were either unrelated to the geotechnical phase of the project or extremely minor that their environmental impacts were negligible, were excluded from the system boundary. Such items were downstream impacts (to end-of-life), manufacturing and maintenance of equipment, the site, and main offices, and wastage disposal (above 10 km). The included and excluded processes are illustrated in Fig. 2.

6. Results and discussion

The CO_2-eq emission of case study projects was analyzed considering that the typical production of piles, DSM, and VR in that ordinary materials (e.g., cement, aggregate, and the like) are implemented and eco-optimized techniques in that environmentally-friendly concerns are taken into account.

The proportions of CO_2 attributed to different constituents (e.g., material, energy, and the like) were approximately constant for a given technique in all three case studies. As shown in Fig. 3, the material has the main contribution to generating CO_2-eq by 92 and 95% in piling and DSM solutions, respectively. Conversely, regarding VR or (DC+VR for case A), 52% belonged to the fuel consumption and only 27% was related to the material (since DC and VR do not use cement).

The total CO_2-eq discharge of the studied projects and the portions of each component are presented in the left three bars of Figs. 4, 5, and 6. The comparison between alternative solutions demonstrated that VR, among the studied techniques, imposes the least burden on the environment while piling is the most harmful with the CO_2-eq emission of approximately 10 times as much as VR. DSM stands between the other two techniques.

Some eco-friendly measures were mentioned in Section 3 for decreasing the environmental impacts of DC, VR, and DSM. Nonetheless, it would be highly difficult, if not impossible, to predict and quantify the efficiency of those potential savings and estimate the influence on the CO_2-eq emission since the impacts strongly rely on soil type, ground reaction, personnel workmanship, consultant and client's consents, and the like. In this study, however, environmental assessments were revised after implementing some quantifiable eco-measures as follows:

- For piling, 70% of cement type I was replaced by GGBS. The production of one ton of cement produces 860 kg whereas the same amount of GGBS generates only 80 kg CO_2-eq. Further, 40% of rebars were assumed to be supplied from recycled steel. New and recycled rebars produce 2,055 and 565 kg CO_2-eq per ton.
- Regarding DSM, 70% of cement was replaced by GGBS.
- And for VR, 50% of aggregates were considered to be recycled/recovered on the site, sourced from recycled concrete or other types of construction by-products. The production of such materials does not emit extra CO_2-eq while that of quarried aggregates produces 4 kg CO_2-eq per ton.

All the above-mentioned alternative materials are considered to be transported from the same distances. Figs. 4, 5, and 6 depict the ecological benefits resulting from employing these eco-friendly materials. The most considerable changes were observed for DSM, where the implemented eco-friendly scheme mitigated environmental loads by 58 – 60%. The applied methods on piling and VR could diminish the CO_2-eq emission by 32 – 36% and 8 – 18%, respectively.

To understand the influences of project conditions on carbon footprints and to be able to make more realistic comparisons, the released quantity of CO_2-eq should be presented not only in total amounts but also in functional units. In this study, the project area, the supported loads, and the supported load multiplied to the penetration depth (drilling depth for piling and improvement depth for DSM and VR) are selected as functional units. Table 2 compares the estimated CO_2-eq of the case studies in total and the units.

In cases A and B, despite having totally different loaded areas, regarding the fact that the applied ground pressures and the penetration depths (for piling, DSM, and VR) were in the same ranges, the CO_2-eq emission per functional unit is reasonably close. The differences are mainly due to different mobilization distances and designs. On the other hand, case C was on a different scale in terms of load and depth, therefore, lighter designs were proposed for all three techniques in the pattern and depth of columns, leading to a decrease in the CO_2-eq emission per square meter and supported load. Hence, carbon emission per unit area and per carried load could not provide meaningful information. In this study, carbon footprints were presented per supported load multiplied by the penetration depth to incorporate the effect of area, load, and depth.

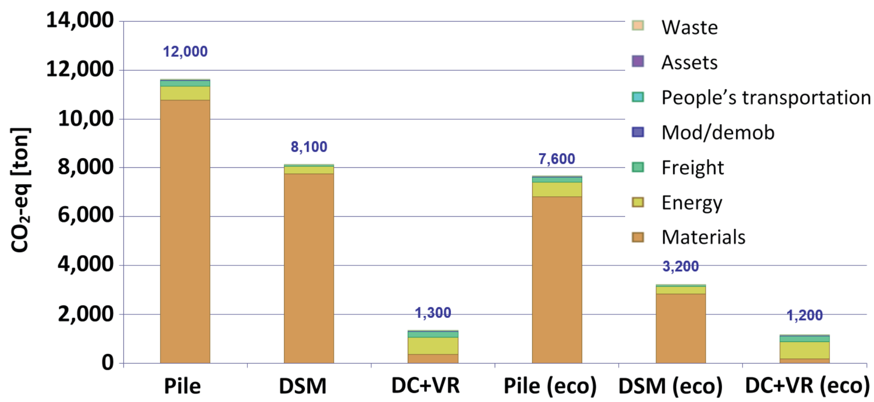

Fig. 4. Case A: CO_2-eq emission of various techniques. The bars with the index "eco" are the analyses of eco-friendly procedures

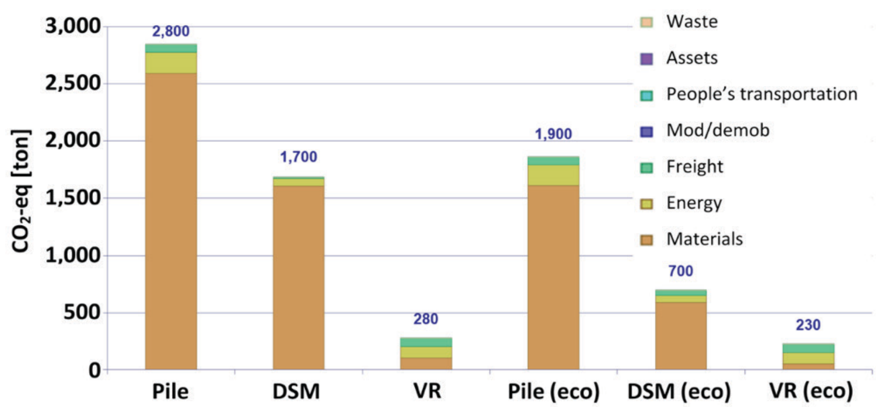

Fig. 5. Case B: CO_2-eq emission of various techniques. The bars with the index "eco" indicate the analyses of the eco-friendly procedures

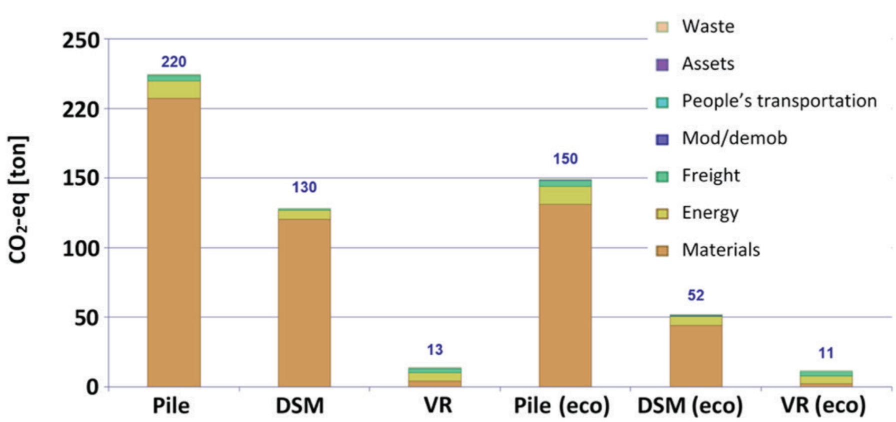

Fig. 6. Case C: CO_2-eq emission of various techniques. The bars with the index "eco" represent the analyses of the eco-friendly procedures

Table 2: Emitted amounts of CO_2-eq in the studied projects and techniques in total and in functional units

Case	Functional Units	Unit	Piling	DSM	VR*	Piling (eco)	DSM (eco)	VR* (eco)
A	Total emission	[ton]	12,000	8,100	1,300	7,600	3,200	1,200
	Per area	[kg/m^2]	1,218	822	132	771	325	122
	Per supported load	[kg/kN]	4.898	3.306	0.531	3.102	1.306	0.490
	Per supported load and depth	[kg/kNm]	0.163	0.207	0.029	0.103	0.082	0.026
B	Total emission	[ton]	2,800	1,700	280	1,900	700	230
	Per area	[kg/m^2]	1,371	832	137	930	343	113
	Per supported load	[kg/kN]	4.930	2.993	0.493	3.345	1.232	0.405
	Per supported load and depth	[kg/kNm]	0.164	0.214	0.025	0.112	0.088	0.020
C	Total emission	[ton]	220	130	13	150	52	11
	Per area	[kg/m^2]	268	159	16	183	63	13
	Per supported load	[kg/kN]	2.981	1.762	0.176	2.033	0.705	0.149
	Per supported load and depth	[kg/kNm]	0.199	0.220	0.022	0.136	0.088	0.019

* For case A: DC+VR

Based on the outcomes, at least, for projects which are similar to studied cases, the average carbon footprints of 0.16 – 0.2 kg/kNm, 0.2 – 0.22, and 0.02 – 0.03 for piling, DSM, and VR, respectively, can be expected when not employing previously explained eco-friendly measures while the average carbon footprints of 0.1 – 0.14, 0.08 – 0.09, and 0.02 – 0.025 kg/kNm for piling, DSM, and VR when applying the measures. Although the emission associated with DSM production per load-depth seems to be in the same range as piling, it should be noted that the required penetration depth of DSM is typically much less (around half) of that in piling.

7. Conclusion

Geotechnical engineers can and should contribute to sustainable designs by adopting environmentally-friendly alternative techniques that minimize the use of energy and the production of CO_2 (e.g., VR or DSM instead of piling where interchangeable) in addition to using recycled or recovered alternative materials or the by-products of other industries instead of new or quarried materials (Gomes Correia et al., 2016).

The CO_2-eq emissions of three real projects, each with three alternative geotechnical techniques, were analyzed in this study using typical and eco-friendly execution procedures. The proposed eco-friendly measures were partially replaced energy consuming materials (i.e., steel, cement, and aggregate) with more sustainable alternatives (i.e., recycled steel, GGBS, and recycled/recovered aggregate). The use of these materials was proved to have significant impacts on the carbon emission of the projects while keeping the same technical quality of works.

As far as alternative solutions are concerned, the environmental impact of piling was roughly 50 – 70% more than that of DSM for typical productions and 130 – 190% for eco-friendly productions. However, VR was found to be the most environmentally-friendly technique. The carbon footprint of piling was around 9 – 17 times as much as VR for typical productions and 6 – 13 times after considering eco-friendly recommendations.

To have a better understanding of the environmental impacts of the studied cases and solutions, carbon emissions were converted to the emitted CO_2-eq per functional unit, among which the "supported load × depth" provided a more realistic picture of the carbon footprint of the products. The estimated values for the carbon emission of each technique may be useful for approximation and preliminary purposes. Nonetheless, all details of the project should be taken into calculation for an accurate CO_2-eq estimation.

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