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Assessment of triple bottom line of sustainability for geotechnical projects

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Abstract

The American Society of Civil Engineers set three pillars of sustainability, the triple bottom line approach, revolving around the environment, economy and equity. This approach is aligned with the Sustainable Development Goals set by the United Nations. Activities undertaken in any construction project must follow this approach and must be audited to validate their impact on sustainability. Geotechnical projects lack an audit/assessment tool encompassing the triple bottom line. Efforts were made to modify SPeAR (Sustainable Project Appraisal Routine) into Geotechnical SPeAR, but the system lacks the quantification scale as used by Environmental Geotechnics Indicators. The study aims to develop a new tool called *Geo-SAT* (Geotechnical Sustainability Assessment Tool), overcoming these limitations, incorporating engineering as a vital pillar. *Geo-SAT* is based on indicators quantified on a scale of 1 (detrimental) to 5 (significantly improved) to assess the impact of actions taken or considered, on sustainability. The total number of indicators developed is 169 out of which 79 are specific to the triple bottom line approach and 90 to engineering. These indicators are generic and can be used for geotechnical projects with the flexibility of exclusion as per the nature of the project. The different fields targeted are dams, foundations, landslides, contaminated site remediation, soil and erosion control, offshore construction and transportation. This tool will serve as a potential code of sustainability for geotechnical projects.

Keywords Triple bottom line · Sustainable Development · Aspects · Indicators · Assessment · Sub-indicators

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Abbreviations

ASCE	American Society of Civil Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme
DQI	Design Quality Indicator
EGI	Environmental Geotechnics Indicators
Geo-SAT	Geotechnical Sustainability Assessment Tool
LCCA	Life Cycle Cost Analysis
LEED	Leadership in Energy and Environmental Design
SD	Sustainable development
SPeAR	Sustainable Project Appraisal Routine
UNSDG	United Nations Sustainable Development Goals

1 Introduction

The depleting resources and the growing environmental awareness, social requirements and the balanced use of economy were the basis of the idea of sustainability. American Society of Civil Engineers (ASCE) therefore introduced the “triple bottom line” criteria, to achieve sustainability in the construction industry. The approach encompasses economy, equity and environment generally termed as 3 Es (Fig. 1). Based on four priorities for change, ASCE developed a five-year roadmap to implement Sustainable Development (SD) in Policy Statement 418 ASCE (2013).

Numerous studies have been conducted contributing to SD. Some of the works are focused on geosynthetics, material reuse and recycling (Pham 2020), and some contribute to the use of underground space (Broere 2016). Geohazards mitigation is an important aspect (Kuriqi et al. 2016; Muceku et al. 2016; Yasuhara et al. 2012). Similarly, new technologies are gaining the highlight of researchers such as biotechnology (Omoregie et al. 2018) and nanotechnology (Taha and Alsharef 2018).

Recycled material and alternate material usage are often considered to be contributing to sustainability, but it is not always the case. Different factors of sustainability should be considered as well while doing so such as the economic viability, long-term performance, environmental impacts, acceptance by the community and many more. The local market must also not be disrupted due to a complete shift from traditional methods to innovative techniques, which ultimately will affect the community and the ongoing economic aspects of their life. Similarly, the use of underground space seems to be a smart and intelligent

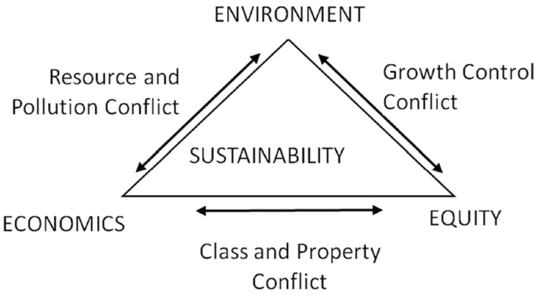


Fig. 1 Aspects of sustainability (Mazmanian and Kraft 2009)

way to achieve sustainability but, in some cases, psychological issues of community such as security threats and their aesthetic sense may not allow such.

Assessment of activities must be carried out to confirm and authenticate their effectiveness in achieving the SD goals. This is in line with the United Nations Sustainable Development Goal (UNSDG) 12, specifically target 12.B (Johnston 2016). Different approaches have been used to do so, some being anthropogenic as "Weak Sustainability" (Arrow et al. 2003) and others multi-dimensional revolving around the 3 Es as "Strong Sustainability" (Daly 2005). Seager et al. (2012) developed an approach termed as "Sustainability Science" to cope with the complexity of engineering problems. Rating systems were developed in civil engineering as well such as Building Research Establishment Environmental Assessment Method (BREEAM) (BRE 2014), Leadership in Energy and Environmental Design (LEED) (HOK et al. 2008), Environmental and Whole Life Cost Estimating Tool (ENVEST 2) (Watson et al. 2004), Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL) (BRE 2018), Design Quality Indicator (DQI) (Gann et al. 2003), EnVision (ISI 2015), Environmental Geotechnics Indicators (EGI) (Jefferson et al. 2007) and SPeAR (ARUP 2010). A few of these systems are unidimensional and others multi-dimensional.

Geotechnical engineering has different dynamics and specifics as compared to other fields of civil engineering. Being heterogeneous, geotechnics carries uncertainties far more complicated than any other civil engineering branch. As identified by Misra and Basu (2011) and Basu et al. (2015), geotechnical engineering lacks a dedicated assessment tool. A thorough review of the available literature on sustainability and assessment tools confirmed that no tool is specific to geotechnical projects, and therefore, a new tool must be developed. The review focused on understanding the technical dynamics of geotechnics, sustainability and existing assessment tools, and their potential applicability to geotechnical projects.

The study aims to develop one such tool that is dedicated to geotechnical projects, encompassing the 3 Es of sustainability, with the inclusion of Engineering as suggested by Basu et al. (2015) to modify it to 4 Es (Fig. 2). The objectives of this study are to identify the areas of geotechnical projects that need to be assessed, develop indicators for these areas, quantify them on a scale for coherent assessment throughout and evaluate Pakistan's construction industry that whether any assessment tool is used specifically to geotechnics.

The new tool developed is named *Geo-SAT* (Geotechnical Sustainability Assessment Tool). This paper focuses on the assessment of social, economic and environmental aspects of sustainability. The system differentiates among these aspects and therefore has an advantage over others.

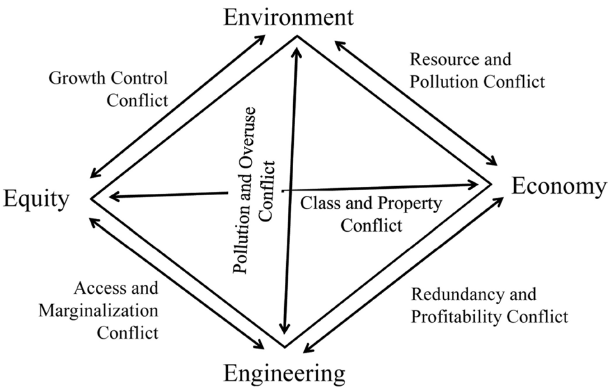


Fig. 2 Triple bottom line approach with associated conflicts with the inclusion of engineering (Basu et al. 2015)

2 Available sustainability assessment tools

Several assessment techniques/tools have been developed within the past few decades. Some can be implemented at all stages and some are restricted to only a few phases of construction. Some are generic and others project-specific, some unidimensional and others multi-dimensional. Two systems that are well established are the Environmental Management System and Corporate Social Responsibility (Braithwaite 2007). But both these tools are unidimensional. Therefore, new tools were developed in the construction industry as identified in Sect. 1, to make sure that they are multi-dimensional and assess all the complexities of engineering ventures. A summary of a few well-developed multi-dimensional tools as SPeAR (Holt 2010) and EnVision (ISI 2015) is presented in this section.

2.1 SPeAR

Sustainable Project Appraisal Routine (SPeAR) was developed by ARUP (2010). It is a software-based assessment tool. The aim is to incorporate different stakeholders into understanding the concept of sustainability. The system is based on the environmental programs of the United Nations (UN) and the indicators defined by the UK government. The results are shown on a figure similar to a dartboard having shaded concentric circles intending to hit the center (Fig. 3). The closer the indicator is to the center, the more sustainable it is. The rating is done on a scale of -3 to $+3$, from least to most sustainable aspects,

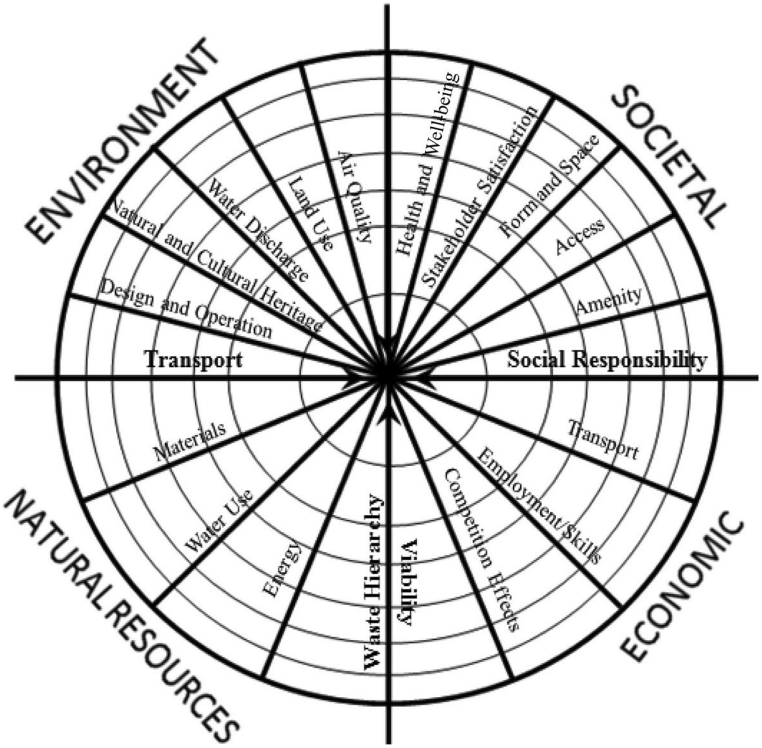


Fig. 3 SPeAR template (Basu et al. 2015)

respectively. A score of -3 (worst case) relates to bare compliance and 0 represents the best practices currently available. $+3$ represents the benchmarks set to meet sustainability standards in each field by experts. It divides the project into 4 main categories, i.e., environment, natural resources, societal and economic. Each category is subdivided into further categories as can be seen in Fig. 3. Environment and society have 6 sub-categories and economic and natural resources have 4.

2.1.1 Strengths

- SPeAR model can be applied at any stage within the project from planning to long-term monitoring. It gives you feedback throughout that how much has one been able to achieve the set goals and identify where one has missed. In other words, it gives you a framework for continuous improvement and assessment.
- It does not compare one project with another, but instead compares the different aspects within a project, thereby considering each project unique.
- It is a method to improve the project in terms of sustainability and not an award system to be asked for.
- It gives the flexibility to modify, add or remove any indicator as per the project's nature and therefore is both generic and technique-specific.

2.1.2 Weaknesses

- A proper assessment team is required for effective results.
- Modifications are required to the indicators to configure it with geotechnical engineering.
- The assessment is generic and not quantified.
- The numbering is based on engineering judgment keeping in mind the best and worst cases as benchmarks.

2.1.3 SPeAR to Geo-SPeAR

The indicators defined by SPeAR are very broad and generic and can be used for assessment of geotechnical projects, but still, there are a few indicators that need to be removed. Holt (2010) removed 16 of 122 indicators, as they were based on advanced level business decisions. The indicators removed are given in Table 1. Some indicators were modified and some added. Modified and new indicators are given in Table 2. Despite these works, the weaknesses persist and therefore suggest the development of a new tool.

2.2 EnVision

Zofnass Program for Sustainable Infrastructure developed EnVision in 2015. It is a decision-making tool based on the triple bottom line approach (ISI 2015). EnVision is based on 5 categories, i.e., Leadership, Quality of Life, Climate and Risk, Natural World and Resource allocation. These categories are assessed using 60 sustainability criteria. Each criterion is assessed using 5 scales, i.e., Restorative, Conserving, Superior, Enhanced and Improved. The complete points scorecard is shown in Fig. 4.

Table 1 Indicators removed from SPeAR by (Holt 2010)

Category	Indicator
Access	Housing types, key facilities, telecommunications,
	Education and lifelong learning
Social responsibility	Donations to voluntary and community organizations
	Global supply chain
Stakeholder satisfaction	User controls
	Customer satisfaction
Water discharge	Sewage treatment
Viability	Operations management tools and technologies
	Service contracts
Transportation	Pedestrian/bicycle facilities
	Public transport infrastructure
	Green transportation
Health and wellbeing	Provision of support facilities
Form and space	Public and private realm

2.2.1 Strengths

- The system is based on a qualitative and quantitative rating scheme specific to civil engineering.
- The system focuses on the resilient and long-term impacts of decisions on the environment and society.
- The system targets to lower the costs and time of the owner and community and makes sure the stakeholders' communication is enhanced.

2.2.2 Weaknesses

- The system has no marginal distinction between different aspects of sustainability.
- The scale defined for all criteria is different and not consistent throughout. A few criteria lack a complete scale.
- The system is weak in assessing the engineering activities carried out during the project life cycle.
- The system is generic and does not target geotechnical projects and therefore requires modifications.

2.3 Need of a new framework

The different aspects of sustainability and the multiple assessment tools available in the construction industry were studied. It was concluded that geotechnical engineering needs the development of a new sustainability assessment tool. The tool should focus on the achievement of SD goals related to the diverse geotechnical dynamics. This paper focuses on the assessment of the triple bottom line approach specific to geotechnical

Table 2 Indicators modified by Holt (2010)

Category	Indicator	Optimum case	Worst case
Social responsibility	Responsible resourcing	To ensure the sustainability of materials' source	No consideration given to optimum case
	Ethical international trade	Ethical codes followed in materials' resourcing	
	Environmentally friendly resourcing	To make sure that trading of material is eco-friendly	
	Social Fairtrade	Ensuring Fairtrade	
Stakeholder satisfaction	Air quality	Compliance to local and national codes	
	Employee Satisfaction	During design and construction	
	Client satisfaction	Effective collaboration b/w geotechnical engineer, other specialists and client's response valued	
	Occupant satisfaction	Finest maintenance practice followed	
Viability	Efficiency of design	LCA incorporated	
	Adequate site investigation	Investigations incorporating safety and effectiveness	
Competition effects	Marketing effects	Convincing the client to incorporate sustainability in design and the advantages thereafter explained	
Form and space	Communal/circulation areas	Better circulation area provided to workers during construction	
	Internal and external security	Secure construction area along with community's safety	
	Lighting	Better lighting during construction to workers using renewable resources	
Health and wellbeing	Deliver key health targets	Health of workforces considered	
	Occupational safety	Finest maintenance rehearses followed	
	Conditions of work	Provision of suitable amenities to workers on-site	

			IMPROVED	ENHANCED	SUPERIOR	CONSERVING	RESTORATIVE
QUALITY OF LIFE	PURPOSE	QL1.1 Improve community quality of life	2	5	10	20	**25**
		QL1.2 Stimulate sustainable growth and development	1	2	5	13	**16**
		QL1.3 Develop local skills and capabilities	1	2	5	12	**15**
	WELLBEING	QL2.1 Enhance public health and safety	2	—	—	**16**	
		QL2.2 Minimize noise and vibration	1	—	—	8	**11**
		QL2.3 Minimize light pollution	1	2	4	8	**11**
		QL2.4 Improve community mobility and access	1	4	7	**14**	
		QL2.5 Encourage alternative modes of transportation	1	3	6	12	**15**
		QL2.6 Improve site accessibility, safety and wayfinding	—	3	6	12	**15**
	COMMUNITY	QL3.1 Preserve historic and cultural resources	1	—	7	13	**16**
		QL3.2 Preserve views and local character	1	3	6	11	**14**
		QL3.3 Enhance public space	1	3	6	11	**13**
		Maximum QL Points:				**181***	
LEADERSHIP	COLLABORATION	LD1.1 Provide effective leadership and commitment	2	4	9	**17**	
		LD1.2 Establish a sustainability management system	1	4	7	**14**	
		LD1.3 Foster collaboration and teamwork	1	4	8	**15**	
		LD1.4 Provide for stakeholder involvement	1	5	9	**14**	
	MANAGEMENT	LD2.1 Pursue by-product synergy opportunities	1	3	6	12	**15**
		LD2.2 Improve infrastructure integration	1	3	7	13	**16**
	PLANNING	LD3.1 Plan for long-term monitoring and maintenance	1	3	—	**10**	
		LD3.2 Address conflicting regulations and policies	1	2	4	**8**	
		LD3.3 Extend useful life	1	3	6	**12**	
		Maximum LD Points:				**121***	
RESOURCE ALLOCATION	MATERIALS	RA1.1 Reduce net embodied energy	2	6	12	**18**	
		RA1.2 Support sustainable procurement practices	2	3	6	**9**	
		RA1.3 Use recycled materials	2	5	11	**14**	
		RA1.4 Use regional materials	3	6	9	**10**	
		RA1.5 Divert waste from landfills	3	6	8	**11**	
		RA1.6 Reduce excavated materials taken off site	2	4	5	**6**	
		RA1.7 Provide for deconstruction and recycling	1	4	8	**12**	
	ENERGY	RA2.1 Reduce energy consumption	3	7	12	**18**	
		RA2.2 Use renewable energy	4	6	13	16	**20**
		RA2.3 Commission and monitor energy systems	—	3	—	**11**	
	WATER	RA3.1 Protect fresh water availability	2	4	9	17	**21**
		RA3.2 Reduce potable water consumption	4	9	13	17	**21**
		RA3.3 Monitor water systems	1	3	6	**11**	
		Maximum RA Points:				**182***	
NATURAL WORLD	SITING	NW1.1 Preserve prime habitat	—	—	9	14	**18**
		NW1.2 Protect wetlands and surface water	1	4	9	14	**18**
		NW1.3 Preserve prime farmland	—	—	6	12	**15**
		NW1.4 Avoid adverse geology	1	2	3	**5**	
		NW1.5 Preserve floodplain functions	2	5	8	**14**	
		NW1.6 Avoid unsuitable development on steep slopes	1	—	4	**6**	
		NW1.7 Preserve greenfields	3	6	10	15	**23**
	LAND & WATER	NW2.1 Manage stormwater	—	4	9	17	**21**
		NW2.2 Reduce pesticide and fertilizer impacts	1	2	5	**9**	
		NW2.3 Prevent surface and groundwater contamination	1	4	9	14	**18**
	BIODIVERSITY	NW3.1 Preserve species biodiversity	2	—	—	13	**16**
		NW3.2 Control invasive species	—	—	5	9	**11**
		NW3.3 Restore disturbed soils	—	—	—	8	**10**
		NW3.4 Maintain wetland and surface water functions	3	6	9	15	**19**
		Maximum NW Points:				**203***	
CLIMATE & RISK	EMISSIONS	CR1.1 Reduce greenhouse gas emissions	4	7	13	18	**25**
		CR1.2 Reduce air pollutant emissions	2	6	—	12	**15**
	RESILIENCE	CR2.1 Assess climate threat	—	—	—	**15**	
		CR2.2 Avoid traps and vulnerabilities	2	6	12	16	**20**
		CR2.3 Prepare for long-term adaptability	—	—	—	16	**20**
		CR2.4 Prepare for short-term hazards	3	—	10	17	**21**
		CR2.5 Manage heat islands effects	1	2	4	**6**	
		Maximum CR Points:				**122***	
		Maximum TOTAL Points:				**809***	

* Not every credit has a restorative level. Therefore totals include the maximum possible points for each credit whether conserving or restorative.

Fig. 4 Points scorecard for EnVision (ISI 2015) engineering. The tool developed is called *Geo-SAT* (Geotechnical Sustainability Assessment Tool).

3 Methodology to develop a framework for Geo-SAT

Available literature pertinent to sustainability and geotechnical engineering was reviewed to analyze the application potential of tools to geotechnics. Efforts were made to review the impact of past and current construction practices and the current decision-making on sustainability in the field of geotechnics. The field experience of the authors gained from several projects was also taken advantage of. The recommendations of different researchers to achieve sustainability were also considered. Using this approach, indicators were developed alongside a quantifiable scale. The complete details of the works studied for review and development of this tool are shown in Table 3. A questionnaire survey based on multiple questions was conducted in Pakistan. The survey focused on the investigation of the literature findings, i.e., practices followed, and if any tool specific to geotechnics was used (Fig. 5). The questionnaire was divided into sections based on demographic information and 6 stages of a project, i.e., feasibility, design, construction, etc. A total of 44 questions were asked. Each question was based on a scale of 1 (harmful) to 5 (significantly improved), showing the impact of activities carried out in Pakistan on the sustainability. One question was specific to the use of any sustainability assessment tool.

4 Results and discussion

Eighty-two responses from 70 firms associated with construction activities in Pakistan participated in the survey. All these firms were targeting different phases of construction (Fig. 6). The survey reflected the current practices followed in Pakistan and understands their impacts on sustainability. Based on the expertise and experiences, the respondents confirmed that only 15.9% of the firms used sustainability assessment techniques and the rest do not use any (Fig. 7). The tools used were not specific to geotechnics and thereby indicate the need for a new system.

4.1 Framework to develop Geo-SAT

Based on 4 Es, Geo-SAT was developed using detailed literature specific to geotechnics, sustainability and assessment tools. The complete details of the works studied are shown in Table 3. The framework was based on 5 sections called "aspects," i.e., General Information, Engineering, Social, Environmental and Economy. Each section was then subcategorized into "stages" which are based on "indicators," which are further grounded on "sub-indicators." The framework is based on a total number of 169 sub-indicators and 79 focusing on the triple bottom line. The impact of each indicator on sustainability is assessed using a Likert scale of 1–5, i.e., detrimental, reduced, neutral, improved and significantly improved. The scale for 16 of these indicators was kept the same as of EGI. Sixty-three new indicators and scales were developed as a whole.

Table 3 Sources referred to develop indicators and sub-indicators for social, environmental and economic aspects

Indicator	Source	Comments/remarks
Social aspect of sustainability		
Community stage	Jefferson et al. (2007), McGregor and Roberts (2003), ARUP (2010), ISI (2015), Vanclay (2002), Srinivasan (2001), Kagan (2014), Johnston (2016)	9 sub-indicators
Security, land use and livelihood stages	McGregor and Roberts (2003), ARUP (2010), ISI (2015), Jefferson et al. (2007); Vanclay (2002), Tilt et al. (2009), HSE (2015), Lerer and Scudder (1999), Johnston (2016)	7 sub-indicators
Infrastructure and political	McGregor and Roberts (2003), ARUP (2010), ISI (2015), Vanclay (2002), Brundtland (1987), Tilt et al. (2009), Basu et al. (2015), Kibler et al. (2012), Khan et al. (2014), Kuriqi et al. (2016)	11 sub-indicators
Geoethics	Jefferson et al. (2007), Peppoloni and Di Capua (2012), Basu et al. (2015)	2 sub-indicators
Resettlement	Vanclay (2002), McGregor and Roberts (2003), ARUP (2010), Kirchherr and Charles (2016), Kirchherr et al. (2019), Scudder and Colson (2019)	2 sub-indicators
Environmental aspect of sustainability		
Soil and land	Jefferson et al. (2007), ARUP (2010), ISI (2015)	10 sub-indicators
Biodiversity	ISI (2015), Tilt et al. (2009)	2 sub-indicators
Waste	McGregor and Roberts (2003), ARUP (2010)	4 sub-indicators
Water and energy	ARUP (2010), ISI (2015), Jefferson et al. (2007)	9 sub-indicators
Climate change, air quality, noise and light	Jefferson et al. (2007), Harris (2005), Yasuhara et al. (2012)	10 sub-indicators
Economic aspect of sustainability		
Economic Effect	Basu et al. (2015), Raymond et al. (2017), Horvath (2003), Praticò et al. (2011), Jefferson et al. (2007), ARUP (2010)	6 sub-indicators
Facilities management and labor standards	ARUP (2010)	5 sub-indicators

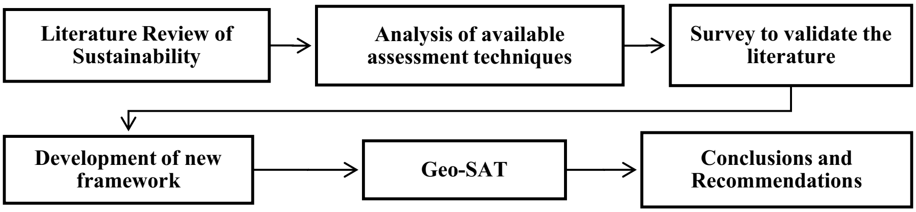


Fig. 5 Methodology to develop a new framework for geotechnical projects

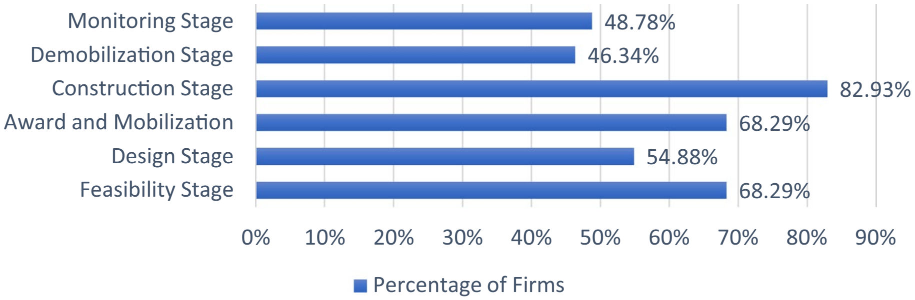


Fig. 6 Survey results of construction activities carried out by respondents

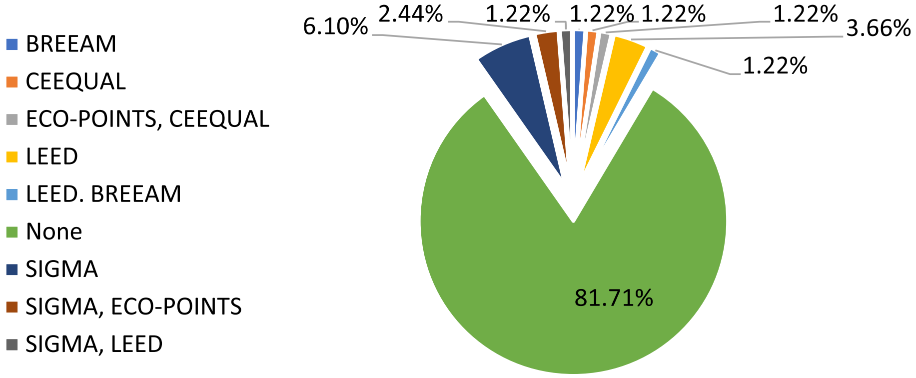
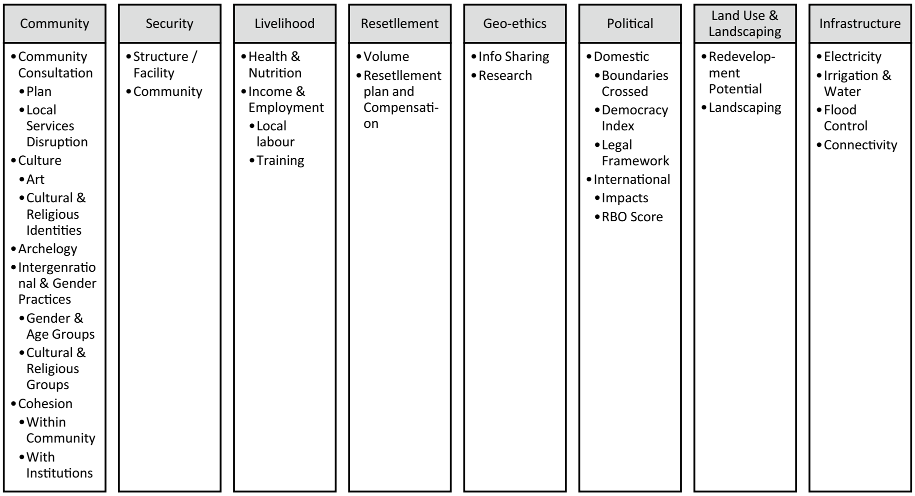


Fig. 7 Survey results related to the use of sustainability assessment tool in Pakistan

4.1.1 Social aspect of Geo-SAT

Vanclay (2002) identified 80 impacts related to the social aspect of sustainability in general. Using the works of researchers enlisted in Table 3 and the practices followed in Pakistan, a total of 31 sub-indicators specific to geotechnics were derived and quantified. These were divided into eight broad stages (Fig. 8). These indicators along with their impacts are summarized in Tables 4, 5, 6 and 7.



Community	Security	Livelihood	Resettlement	Geo-ethics	Political	Land Use & Landscaping	Infrastructure
• Community Consultation • Plan • Local Services Disruption • Culture • Art • Cultural & Religious Identities • Archelogy • Intergenrational & Gender Practices • Gender & Age Groups • Cultural & Religious Groups • Cohesion • Within Community • With Institutions	• Structure / Facility • Community	• Health & Nutrition • Income & Employment • Local labour • Training	• Volume • Resettlement plan and Compensation	• Info Sharing • Research	• Domestic • Boundaries Crossed • Democracy Index • Legal Framework • International • Impacts • RBO Score	• Redevelopment Potential • Landscaping	• Electricity • Irrigation & Water • Flood Control • Connectivity

Fig. 8 Framework for assessment of the social aspect of sustainability

S-01 to S-02: The community must be consulted before the start of any project. This ensures their point of view and helps understand what to expect from the project. Not taking community on board is one of the reasons that the majority of the projects fail to safeguard the utilities being used by the communities.

S-03 to S-05: The essence of any community is its culture and the archelogy. These resources must be protected as these are a vital part of sustainability. This was recognized by the Asia-Europe Foundation in 2008 by initiating a program call Connect2Culture. Similarly, in 1996, "Villette-Amazone" was organized in Paris by the French Committee for Environment and Sustainable Development to combine architecture and ecological urbanism with projects (Kagan 2014). UNSDG target 11.4 aims at this indicator.

S-06 to S-09: The UNSDG 5 targets "gender equality" to end all sorts of gender discrimination. Equal opportunities are further targeted in indicator 5.5 of UNSDGs. Therefore, the approaches made in any developed society or community should not be gender or age specific. They should target multiple groups. Also, the UN declaration 34 in 2030 Agenda for SD focuses on the cohesion in a community. Table 4 summarizes indicators S-01 to S-09.

S-10 to S-16: Once the facility is constructed (and during construction as well), it should be safe against any threats and must provide safety to the community as well. This is in line with UN declaration 34 in 2030 Agenda. It should not have harmful effects on the health of the occupying species. It should have a disease control program especially in the case of communicable diseases as highlighted in UNSDG target 3.3. Also, during its lifetime, it should be a source of income and employment for the communities (UNSDG targets 9.2 and 12.8). At the salvage stage, the facility advisably should have redevelopment potential and be used in the future.

Table 5 summarizes indicators S-10 to S-16.

Table 4 Community stage: social aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Community consultation						
S-01	Is there a community consultation plan?*	Consultation avoided actively	None	Basic	Detailed using single medium	Detailed using multiple media
S-02	Local community services disruption*	Major utility lost on more than one occasions	Major utility lost on one occasion	Major utility lost but community informed	Minor utility lost and community informed	No services disrupted using proper management
Culture						
S-03	Is public art considered in the project?	Public art removed or destroyed	No consideration given	Some features protected	All features protected	Investments made to enhance public art that are accessible to all
S-04	Does the project protect cultural and religious identities?	Significant loss to identities along with cultural and religious facilities causing negative social impacts	Local identities undermined due to the failure of not recognizing these identities	Local identities and facilities identified	Local identities and facilities protected	Creative design implemented to reinforce identities and facilities
Archaeology and local heritage						
S-05	Are the archeological concerns identified and protected?	No measures taken causing a loss of such resources	Measures taken to reduce the loss of such resources	Measures taken to protect such resources	Retention and restoration of such resources	Protection and enhancement of such resources using appropriate measures such as reclamation, preservation in situ, analysis and design
Intergenerational and gender practices						
S-06	Does the project provide equal job opportunities to all genders and age groups?	Only one gender and specific age group	Only one gender but different age groups	Major focus on one gender but specific age group	Major focus on one gender but different age groups	Equal opportunities for all genders and all age groups

Table 4 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
S-07	Does the project provide equal job opportunities to all cultural and religious groups on merit?	Only a specific culture or religion targeted due to local pressure	Nepotism favoring specific religion or culture	Job opportunities provided regardless of culture and religion	Job opportunities provided regardless of culture and religion on merit	Job opportunities provided regardless of culture and religion on merit with bonuses for employees putting in extra effort
Cohesion						
S-08	Does the project retain or enhance integration between multiple groups within the community?	Project creates tensions, fear and conflict in the community	Disintegration and impartiality of the community	No contribution to community interaction	Project retains the interaction between different groups of the community	Project enhances community cohesion by allowing them to meet new people, encouraging closer relations and spreading awareness of understanding other groups
S-09	Does the project help in enhancing the communications and linkages of the local community with different organizations (government and non-government)?	Worsens the situation with both government and non-government institutions	Worsens the situation with either government or non-government institutions	No effect on linkages with both government and non-government institutions	Improves linkages with either government or non-government institutions	Improves linkages with both government and non-government institutions

*Indicator retained from Jefferson et al. (2007)

Table 5 Security, land use and livelihood stages: social aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Security: structure/facility						
S-10	Have measures been taken to enhance the security of the structure/facility built to counter un-natural activities, i.e., terrorism, attacks, etc.?	No plan and measures in place	Plan drafted by non-dedicated teams but not effective	Plan drafted by dedicated teams but not effective	Plan drafted by dedicated teams and measures taken to cover major sections/areas of the facility	Plan drafted by dedicated teams and measures taken to cover all sections/areas of the facility
Security: community						
S-11	Have measures been taken to enhance security such as increased visibility, clearly distinguished public and private areas, etc.?	Areas exposed to major security threats causing an increase in the cost of crime to community and organizations	Public areas underused with no clear distinction between private and public spaces	Clearly distinguished areas with major public area use	Active public areas created with strong natural surveillance securing private areas	Dedicated design team ensuring maximum surveillance using Crime Prevention Through Environmental Design (CPTED)
Livelihood: health and nutrition						
S-12	Does the project cause to create habitats for species causing different diseases and what measures have been taken to overcome these health-related challenges?	Waterborne diseases caused by no measures taken to control them	Public sanitation improved and clean water supplied to communities	Public sanitation improved and clean water supplied to communities along with regular flushing of streams and irrigation canals	Disease control programs initiated along with the provision of clean water and improved public sanitation schemes	Disease control programs initiated and fish species breeding implemented that eat species causing such diseases

Table 5 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Land use						
S-13	Site's redevelopment potential*	None	Very low	Low	High	Very high
S-14	Site usability in future*	Harmful	Queries persist and stay unanswered	No effect	Yes	Very suitable
Livelihood: income and employment						
S-15	Percentage of local labor employed/hired*	No local labor employed	< 10% of the labor force	10–25% of the labor force	25–50% of the labor force	> 50% of the labor force
S-16	Percentage of employees that undergo awareness trainings?	< 10%	10–50%	50–75%	75–90%	> 90%

*Indicator retained from Jefferson et al. (2007)

Table 6 Infrastructure and political stages: social aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Infrastructure: electricity						
S-17	Electricity provided	No electricity produced	Electricity produced for running the facility	Electricity produced only for close-by local communities	Electricity produced only for provincial/state-level use	Key electricity producer for national benefits
Infrastructure: irrigation and water						
S-18	Irrigation potential	Significantly detrimental to existing irrigation system	Partially detrimental to existing irrigation system	No impact to the existing irrigation system	Improves existing irrigation system but sediment flow is disturbed	Improves existing irrigation system with efforts made to optimize sediment flow down streams
Infrastructure: flood control						
S-19	Is there a flood control potential in the project?	Detrimental to existing flood control programs	No impact on existing flood control programs	Partially improves the existing flood control programs	Significantly improves the existing flood control programs	Serves to be the pioneer/only flood control program
Infrastructure: connectivity						
S-20	Does the project enhance connectivity?	Significant negative impacts causing hindrances in connectivity	Minor hindrances caused in connectivity	No consideration given	Connectivity improved with only key facilities	Connectivity improved with a majority of the facilities causing an improved interaction between communities
S-21	Is the project located near any navigable waterways or are any waterways upgraded to be navigable as part of the project?	No consideration given despite existing facilities	Existing waterways used	Existing waterways used and fuels having a lesser impact on the environment used for transport	Accessibility improved	Waterways will be used by passengers as well as for freight movement

Table 6 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Political: domestic						
S-22	Boundaries Crossed	Multiple national boundaries	Single national boundary	Multiple provincial boundaries	Single provincial boundary	No boundaries crossed
S-23	Consent of boundaries crossed	Majority of national boundaries crossed causing tension among the communities	Some of the close-by national boundaries crossed causing tension among the nearby communities	Consent of only local communities taken	Consent of all communities taken	Consent of all communities taken and considered in decision making improving regional cooperation
S-24	Democracy Index	Decision processes are closed	Government management capacity is limited	Civil dialogue is constrained	Decision processes are open with robust government management capacity	Civil dialogue is open and active
S-25	Robustness of legal framework	No laws in place	Local community laws in place	Provincial/state level laws in place	National level laws in place	Multi-national laws in place
Political: international						
S-26	Has the project considered international political impacts?	No consideration given	Considered but not involved	Considered and planned internally to avoid conflicts	Considered and planned internally to avoid conflicts and other parties informed	All the concerned international parties involved in the feasibility stage and a mutual agreement reached to ensure international stability
S-27	River Basin Organizations (RBO) Score	No awareness	Not considered	Considered but no assessment carried out	Assessment carried out covering only critical aspects	Complete assessment covering all aspects

S-17 to S-21: Keeping in mind the alarming climate changes and the threats associated, the structure or facility must provide services such as irrigation, flood control, connectivity, etc. Efforts must be made to combat disasters and reduce social losses (UNSDG targets 11.5 and 15.3). Similarly, accessibility and connectivity not be compromised (UNSDG target 11.2).

S-22 to S-27: Larger structures often face political issues and therefore must be catered during the planning stages. A few such examples are Kalabagh Dam in Pakistan facing domestic political issues (Khan et al. 2014) and the continuous conflict between India and Pakistan since 1960, most popularly called as "Indus water treaty" (Biswas 1992; Kalair et al. 2019). The indicators developed to assess activities related to these concerns are given in Table 6.

S-28 to S-29: Information must be shared and be readily available for the community. This information helps in increasing the connectivity and the cohesion among communities. Majority of the researchers face this difficulty of accessing data in Pakistan. The authors too faced such difficulties. Therefore, efforts must be made to help researchers carry out research activities and help grow the people associated.

S-30 to S-31: Large dams have caused massive relocations. Reports suggest a total number of almost 80 million (Kirchherr et al. 2019). This resettlement must be planned and should have a grievance mechanism to accommodate the social insecurities of people displaced. The indicators S-28 to S-31 are given in Table 7.

4.1.2 Environmental aspect of Geo-SAT

The environmental aspect was subdivided into ten stages as shown in Fig. 9 and was developed using 37 different sub-indicators. The indicators and their effects on sustainability for each stage of sustainability are summarized in Tables 8, 9, 10 and 11.

En-01 to En-10: Contaminated land remediation projects need to be assessed by the technique-specific indicators developed by Jefferson et al. (2007) for EGI (UNSDG target 3.9). Erosion and sediment control are one important aspect of geotechnics. These must be met with a plan thoroughly drafted as a report along with all the relevant drawings. The plan must include inspections and monitoring activities. The project must also ensure the protection of local habitats of occupying species and should not be a habitat to harmful species. The indicators developed to assess activities related to these concerns are given in Table 8.

En-13 to En-18: The waste associated with any project during construction and operation must be cleared through the use of a plan, including hazardous or special waste (UNSDGs targets 6.3, 11.6, 12.4 and 12.5). Secondly, the landscape and indoor environment must provide a pleasing environment with maximum benefits to the occupants and nearby community. The indicators developed to assess activities related to these concerns are given in Table 9.

En-19 to En-27: Water is the most essential compound for all living organisms. Maintaining the aquifers, reducing the use of clean water on construction projects and its efficient use via monitoring and avoiding pollution, is necessary (UNSDG targets 6.3–6.6). Keeping in mind the depleting resources and the impacts of fossil fuels as a source of energy, measures are required to control their usage and should be used efficiently. Monitoring is required and awareness must be spread among the

Table 7 Geoethics and resettlement stages: social aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
GeoEthics: information sharing						
S-28	Information plan with the local community*	Actively avoids interaction	None	Basic	Detailed using single medium	Detailed using multiple media
GeoEthics: research						
S-29	Research works	Actively avoid research activities	Passively avoid research activities	Basic research activities with no funds	Research activities promoted with allocated funds (only for employees)	Research activities promoted with allocated funds (for anyone who wants to carry out research)
Resettlement: volume						
S-30	Does the project result in the resettlement of populations/communities?	Yes, Population displaced/relocated > (5000)0	Yes, Population displaced/relocated > (2500)0	Yes, Population displaced/relocated > (1000)0	Yes, Population displaced/relocated < (1000)0	No displacement/relocation/resettlement
Resettlement: resettlement plan and compensation						
S-31	In case of relocation, has a resettlement plan been implemented and compensations/grievance mechanisms given to displaced people?	Forced displacement and no grievance mechanism in place	Plan in place covering minority of the relocators but no grievance mechanism in place	Plan in place covering a majority of the relocators but no grievance mechanism in place	Plan in place covering all of the relocators but grievance mechanism covers some of the relocators	Plan in place covering all of the relocators and a grievance mechanism in place for all relocators

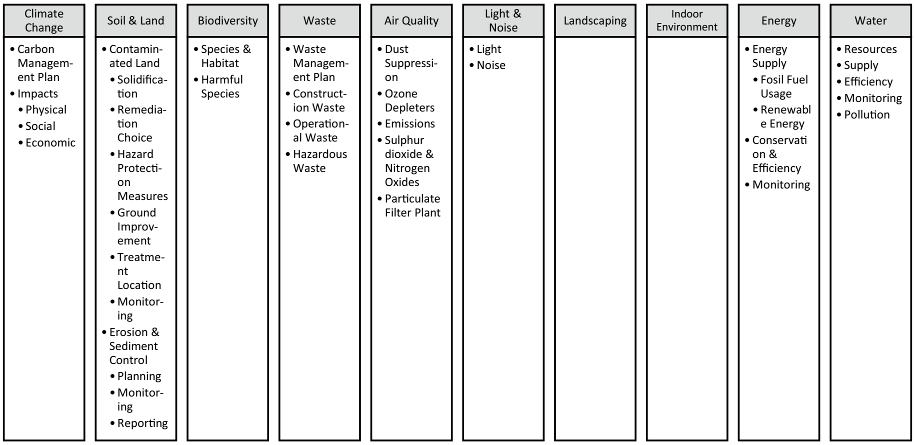


Fig. 9 Framework for assessment of the environmental aspect of sustainability

users to control unsustainable practices (UNSDG targets 7.2, 7.3, 7.A, 7.B and 12.C). The indicators developed to assess activities related to these concerns are given in Table 10.

En-28 to En-37: Any construction project has severe impacts on the air quality because of the emissions. The dust produced limits the visibility and causes diseases as well. The equipment and practices are a major cause of noise pollution as well. As a whole, the surrounding climate is disturbed. Therefore, efforts are required to control all these negative impacts associated with geotechnical projects. The UNSDG targets related to these concerns are 11.6, 11.B, 12.4, 15.2 and goal 13. The indicators developed to assess activities related to these concerns are given in Table 11.

4.2 Economic aspect of Geo-SAT

The economic aspect was subdivided into three stages as shown in Fig. 10 and was developed using 11 different sub-indicators. The indicators and their effects on sustainability are summarized in Tables 12 and 13.

Life Cycle Cost Analysis (LCCA) encompasses all the costs associated with the lifetime of a project. This helps in identifying the weaknesses and benefits of any project. The return on investment period is identified as well, ensuring efficient planning. The distortions faced by the local economy are also identified. The carbon price fluctuations need to be considered along with the timeline of the project and need to be considered in the LCCA. The indicators developed to assess activities related to these concerns are given in Table 12.

The land developed after the construction of the project must give benefits to the community in terms of business or any other infrastructure. Secondly, the structure should be flexible enough to support the changes along its timeline. This can be done using appropriate technologies which will ensure lower operation and maintenance costs. It should be noted that the labor standards must be followed as well during this entire process. The indicators developed to assess activities related to these concerns are given in Table 13.

Table 8 Soil and land and biodiversity stages: social aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Soil and land: contaminated land						
En-01	Contaminant concentration objective*	Significantly lower than guidelines using proven binders	Lower than guidelines using proven binders	Minimum to achieve legislation with proven binders	Minimum to achieve legislation with nonproven binders	Higher than guidelines
En-02	Does the remediation choice leave any issues for ongoing construction?*	Contaminant contained but future piling will be invasive	Contaminant contained but future piling may be invasive	No piling planned	Contaminant contained outside of piling location	Contaminant removed—no restrictions on piling
En-03	Treatment location*	Off-site treatment using open containers for transportation	Off-site treatment using closed containers for transportation	Off-site treatment using closed containers for transportation and reused	On-site treatment and off-site usage	On-site treatment and usage
En-04	Hazard (explosion) Protection Measures*	No controls	Minor efforts	Follows some aspects of HandS	Major aspects of HandS covered	All aspects of HandS covered
En-05	Monitoring (all contaminant types)*	Periodic monitoring required for years	Periodic monitoring required for months	As per planning	Minimum monitoring activities required	No monitoring activities required
En-06	Ground Improvement (GI)*	Build level not reduced to provide adequate cover	Build level reduced to provide adequate cover	No GI planned	Build level increased to provide adequate cover	Working platform provided by the cover

Table 8 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Soil and land: erosion and sediment control						
En-07	Is the project planned in a way causing minimum erosion and controlling the sediments?	No plan implemented	Phased construction plan implemented to reduce the time of soil exposure	Measures taken to reduce the effects (such as vegetation enhanced and gradients reduced)	Erosion and Sediment Control (ESC) plan implemented to cater for all the related aspects (erosion control measures, perimeter control measures, settling control measures and filtration control measures)	ESC designer leads the development and implementation of ESC plan along with contingency plans
En-08	Is/was a report drafted for ESC?	No report drafted	Preliminary report drafted mentioning existing site conditions	Report consists of existing site conditions and critical locations	A detailed report on conditions and design details	A detailed report on conditions, design details and monitoring data
En-09	Are/were detailed drawings for ESC attached?	No drawings attached	Existing vegetation drawings with water resources areas marked	Existing vegetation with water resources areas marked and contour shown	All above + Existing and proposed drainage systems and proposed contours	All above + stockpile and berm data
En-10	Inspections and Performance Monitoring	No monitoring activities carried out	After significant snowmelt events	After every rainfall event	Daily during extended rain or snowmelt periods	Weekly
Biodiversity: protected species and habitats						
En-11	What measures and impacts did the project have on the existing/occupying species and habitats?	No measures taken and undesirable impacts causing a net loss in the overall size and quality of the species and habitats	No measures taken but no net loss caused in the overall size and quality of the species and habitats	No measures required by default	Measures (biodiversity management plan or ecological work plans) taken to protect the habitats for the occupying species	Measures (biodiversity management plan or ecological work plans) taken to protect the habitats for the occupying species with monitoring activities

Table 8 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
En-12	Does the project cause to provide habitat for species that has impacts on human health?	Huge habitats provided for species to grow that harm human health	Small habitats provided for species to grow that harm human health	Habitats provided for new species to grow but with monitoring and compensatory efforts to control harmful impacts	Huge habitats provided for species to grow that have no impact on human health	Huge habitats provided for species to grow that have no impact on human health

*Indicator retained from Jefferson et al. (2007)

Table 9 Waste, indoor environment and landscaping stages: environmental aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Waste: designing out waste						
En-13	Has a site waste management plan (SWMP) been considered?	No SWMP considered	Waste collection areas designated as per local standards	Waste collection areas designated as per BS: (5906) standards	SWMP considered covering some aspects	SWMP considered covering all aspects, i.e., reuse, recovery, off-site construction, efficient procurement, deconstruction and flexibility
Waste: construction waste management plan						
En-14	Has a construction waste management strategy been devised?	No plan in place to decrease construction waste and waste sent to landfills without any monitoring activities	Plan in place to reduce wastes but sent to landfills without monitoring	Plan in place to reuse and recycle the wastes	Plan in place to reuse and recycle the wastes with monitoring activities	A detailed plan drafted at early planning stages covering all aspects of waste management such as efficient material selection, reduction of waste, reuse/recycling of materials, monitoring activities, defining roles, etc.
Waste: waste in operation						
En-15	Operation waste management strategy (OWMS)	No space assigned for waste collection and separation	Space assigned either internally or externally for waste collection and separation	Space assigned along with reuse schemes	Waste reduction plan in place with space for collection and separation	Automated waste collection systems (AWCS) in place with designated spaces for collection and separation. Monitoring activities along with training of occupants carried out

Table 9 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Waste: hazardous/special waste						
En-16	Hazardous waste management plan (HWMP)	Huge amounts of hazardous wastes produced and no plan in place to meet minimum standards	Small amounts of hazardous wastes produced and no plan in place to meet minimum standards	Hazardous wastes produced, separated using labels and disposed off	HWMP in place to reduce wastes. Wastes produced are labeled, stored, managed and disposed of	No hazardous wastes produced
Indoor environment						
En-17	Is the project planned in a mode to create a pleasing indoor environment considering all issues as noise, odor, vibrations, thermal and light, etc.?	No consideration given to the indoor environment	Some issues considered to create a better indoor environment	All issues considered to create a better indoor environment	All issues considered and occupants have control over them	Feedback from occupants is taken to continuously improve the indoor environment
Landscaping						
En-18	Has the landscaping been a primary consideration in the development of the proposals?	No consideration given causing the existing landscape features to degrade	Some features protected	The visual impact is positive	Landscaping fits the scale of the development and the surrounding landscape	Landscaping is considered alongside other issues to achieve maximum benefits from green infrastructure

Table 10 Water and energy stages: environmental aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Water: water resources						
En-19	Water usage vs aquifer system capacity	Aquifer capacity not considered	Unsustainable extraction contributing to depletion of the aquifer system	Water use within current capacity	Water use within current and future capacity	Monitoring system implemented to ensure sustainable water usage for current and future use of communities and surrounding systems
Water: water supply						
En-20	Is the use of mains water reduced?*	No restrictions	Controlled usage	Greywater used—no reuse of process water	Processed water used in combination of mains water	Processed water used in combination of greywater
Water: water efficiency						
En-21	Plan to use water efficiently	No plan in place and no awareness in general	Awareness developed to use water efficiently with no designed/drafted plan	Plan implemented for efficient water usage by occupants	Plan implemented for efficient water usage at all levels such as irrigation, building water, feeding livestock, etc.	Plan implemented covering all aspects along with considerations of water reuse
Water: water monitoring						
En-22	Water monitoring plan	No awareness	No plan implemented	Meters and sub-meters installed to monitor usage	Performance checks made to ensure corrective measures so that water usage can be reduced	Monitoring results used to educate communities along with corrective measures to reduce water usage
Water: water pollution						
En-23	Identification of water pollution sources	No quality targets established	Targets established in line of regulatory bodies	Sources of water pollution identified	Plans implemented to avoid discharge to surface water	Plans implemented to avoid discharge to surface and groundwater

Table 10 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Energy: energy supply						
En-24	Fossil fuel usage*	No restrictions	Limited using awareness training	Limited using action plan	Majority replaced by alternatives	Completely replaced by alternatives
En-25	Use of renewable energy*	None	Considered but not implemented	Considered but not practical	Minor usage	Significant usage
Energy: energy conservation and efficiency						
En-26	Has a plan been implemented to reduce overall energy demand?	Standard technologies used with no plan to reduce energy demand	Standard technologies used with awareness to reduce energy demand	Energy-efficient supplies considered and plan implemented	Energy-efficient supplies, efficient material selection and plan implemented	Facility siting, orientation, form and layout designed in a way to maximize passive heating, cooling and lighting. A plan also implemented to reduce energy demand. Energy-efficient design, processes and materials considered from the planning stage
Energy: energy monitoring						
En-27	Energy Monitoring Plan	No awareness	No plan implemented	Meters and sub-meters installed to monitor usage	Performance checks made to ensure corrective measures so that energy usage can be reduced	Monitoring results used to educate communities along with corrective measures to reduce energy usage

*Indicator retained from Jefferson et al. (2007)

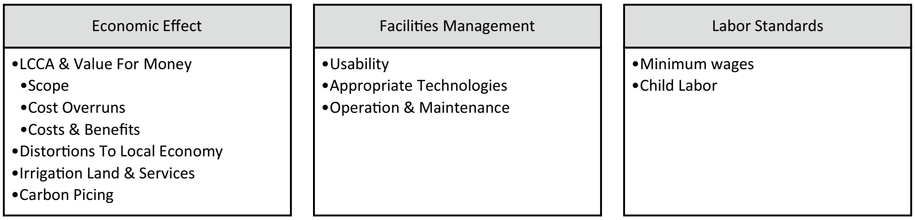
Table 11 Climate change, air quality, noise and light stages: environmental aspect

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Climate change: carbon management plan						
En-28	Calculation of CO_2 emissions and embodied energy (EE)*	Not considered	Considered but not undertaken	Partial analysis for either CO2 or EE	Partial analysis CO2 and EE	Full analysis for CO2 and EE
Climate change: impacts of climate change						
En-29	Has the project considered the social impacts of climate change on the community?	No consideration of short and long-term impacts	No consideration of long-term impacts	Impacts considered for local communities	Impacts considered for local and disadvantaged communities	Impacts considered for communities and infrastructure with a flexible design to adapt to changes over time
En-30	Forestation	Significant deforestation with no compensation	Minor deforestation with no compensation	Deforestation with compensation	No deforestation	Forestation enhanced at the end of the project
En-31	Has the project considered the economic impacts of climate change?	No consideration of short and long-term impacts	No consideration of long-term impacts	Pro-active approach to somehow control such impacts	Pro-active approach to sufficiently control such impacts	Detailed plan implemented to control such impacts
Air quality						
En-32	Dust suppression plan*	None	Plan drafted to reduce dust creation	Water spray dampeners using mains water	Water spray dampeners using greywater	Integrated dust prevention plan implemented
En-33	Sulfur dioxide and nitrogen oxides*	Only coal/oil ratio to gas	Major coal/oil ratio to gas	Equal coal/oil ratio to gas	Minor coal/oil ratio to gas	Clean technology used (e.g., solar, etc.)
En-34	Ozone depleters*	VOCs and NOx allowed to combine	No action	Minor plan to minimize combination	Major actions to control combination	No VOCs allowed to mix
En-35	Particulate filter plant*	None	Minority of plant	Even split	Majority of plant	Entire plant
Light and noise						
En-36	Obstruction of light by smoke*	> 10% of on-site time	10–5% of on-site time	5–1% of on-site time	< 1% of on-site time	No smoke

Table 11 (continued)

S. no.	Indicator	Impact on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
En-37	Noise prevention plan*	Issues ignored actively	Issues ignored passively	Site curfews in force	Majority of plant treated with noise control measures	Integrated noise prevention plan implemented

*Indicator retained from Jefferson et al. (2007)



Economic Effect	Facilities Management	Labor Standards
•LCCA & Value For Money •Scope •Cost Overruns •Costs & Benefits •Distortions To Local Economy •Irrigation Land & Services •Carbon Picing	•Usability •Appropriate Technologies •Operation & Maintenance	•Minimum wages •Child Labor

Fig. 10 Framework for assessment of the economic aspect of sustainability

4.3 Discussions

A new tool was developed for the sustainability assessment of geotechnical projects called Geo-SAT, focusing on the environment, economy, social and engineering aspects. The tool is based on a total of 169 quantifiable indicators, 79 dedicated to the triple bottom line. The number of indicators retained from EGI for social, environmental and economic aspects are 6, 16 and 2, respectively. The scale measures the impact on sustainability on a scale of 1 (detrimental) to 5 (significantly improved) and is coherent throughout. This tool overtakes the weaknesses of other tools such as quantifiable indicators, exclusive division among the aspects, consistent scale, marginal distinction among the different aspects of sustainability and specific to geotechnical projects. Each aspect is divided into stages which are assessed using indicators summarized in Fig. 2. The assessment for each stage is totaled, averaged and plotted on a graph as shown in Fig. 11. The greater the area of the closed polygon, the more sustainable is the project. Efforts were also made to develop a relationship between the Geo-SAT indicators and UNSDGs. The tool helps to assess the different aspects individually but does not classify or rate the project as a whole. It should be noted that the cost analysis of the implementation of Geo-SAT on any project has not been conducted. Case studies should be considered to do so. It is worth mentioning here that the difficulty of accessing data in Pakistan limited the researches to develop and quantify indicators based on literature review only.

5 Conclusions

Within the recent past, efforts have been made in the field of geotechnics to incorporate sustainability such as material reuse and recycling, use of geosynthetics, efficient utilization of underground space, incorporation of biotechnology and nanotechnology, and geohazards mitigation. These activities need to be audited and assessed to measure their impact on sustainability. Geotechnical projects have come up short on a sustainability evaluation technique. To date, the assessment techniques followed in the construction industry fall short on the capability of utilization to geotechnics. This is because available tools are either unidimensional or lack a consistent measurement scale. Some do not consider engineering as a fundamental pillar of sustainability. Although modifications were made to the Sustainable Project Appraisal Routine tool to ensure its applicability to geotechnics, but still the technique did not suffice the need. A questionnaire survey conducted in Pakistan with 82 responses from 70 firms affirmed the deductions of the literature review. Therefore, using

Table 12 Economic effect stage: economic aspect

S. no.	Indicator	Effect on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Life cycle cost analysis (LCCA)						
Ec-01	What is the scope of LCCA?	None carried out	Only agency costs (construction, operation, maintenance, etc.) considered	Agency costs + society costs	Net present value (NPV) considered for all costs involved	Periodic LCCA
Ec-02	Did the project overrun on cost?*	$>10\%$ cost overrun	5–10% cost overrun	On target (within 5% of the cost)	$<5\%$ cost saving	$>5\%$ cost saving
Ec-03	Have all the costs and benefits associated with the project life span been considered?	Only capital costs considered with lowest cost competitive solution chosen	Only capital costs considered with quality solution	Capital and operational costs considered	Capital and operational costs considered with appraisals for economic performance with operational costs saving potential determined	All costs considered with socioeconomic benefits over the life span of the project
Distortions to local economy						
Ec-04	Does the project cause any negative impacts on the local economy particularly low-income groups?	No impacts measured/determined	Annual expenditures given on ad hoc basis without considering ways to maximize local economic benefits	Local services, goods and labor considered	Management strategies in place to overcome negative impacts covering majority of the aspects	Management strategies in place to overcome negative impacts covering all of the aspects
Irrigation and land services						
Ec-05	Irrigation land and services	Significant loss to irrigation land and services	Significant loss to irrigation land or services	Minor loss to irrigation land and services	Minor loss to irrigation land or services	No loss to irrigation land and services
Carbon pricing						
Ec-06	Have the future costs of carbon been considered?	Not considered	Considered for the construction time of the project only	Considered for the construction and monitoring time of the project	Considered for whole life expectancy of the project	Considered for all financial and socioeconomic appraisals throughout the timeline of the project

*Indicator retained from Jefferson et al. (2007)

Table 13 Facilities management and labor standards stage: economic aspect

S. no.	Indicator	Effect on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Usability: facilities management						
Ec-07	Land intended for use by a business or other infrastructure that contributes to local economy*	No influx of new business/infrastructure	< 10% of the site allocated to new business/infrastructure	10–20% of the site allocated to new business/infrastructure	20–30% of the site allocated to new business/infrastructure	> 30% of the site allocated to new business/infrastructure
Appropriate technologies: facilities management						
Ec-08	Are appropriate technologies considered for maximum benefits?	Technologies considered without measuring sustainability impacts	Technologies chosen considering some of the sustainability impacts	Technologies chosen considering all aspects of sustainability	Technologies chosen considering all aspects of sustainability along with training of the majority of individuals	Technologies chosen considering all aspects of sustainability along with training of all the individuals
Whole life flexibility: facilities management						
Ec-09	Has flexibility been considered over the life span of the project for all aspects (reuse, recyclability, minimum refit requirements)?	No awareness of flexibility requirements over the life span of the project	Not considered	Flexibility considered for some aspects	Flexibility considered for all aspects	Flexibility considered for all aspects with systems adaptable to changing conditions to extend life
Operation and maintenance: facilities management						
Ec-10	Are maintenance and operation plans part of the planning?	No plans in place	Only operational plan considered	Maintenance and operation plans considered	Maintenance and operational plans in place with a focus on local skills, goods and services	All plans in place and roles clearly defined in terms of finances available and skills of individuals

Table 13 (continued)

S. no.	Indicator	Effect on sustainability				
		Detrimental	Reduced	Neutral	Improved	Significantly improved
Labor standards						
Ec-11	Are child labor concerns and minimum wages been considered to meet the standards available?	No standards considered	Minimum wages meet local labor standards but child labor still in place	Minimum wages meet local standards and child labor avoided	Minimum wages meet international standards and child labor avoided	Plans in place to improve standards to ensure decent work environ

*Indicator retained from Jefferson et al. (2007)

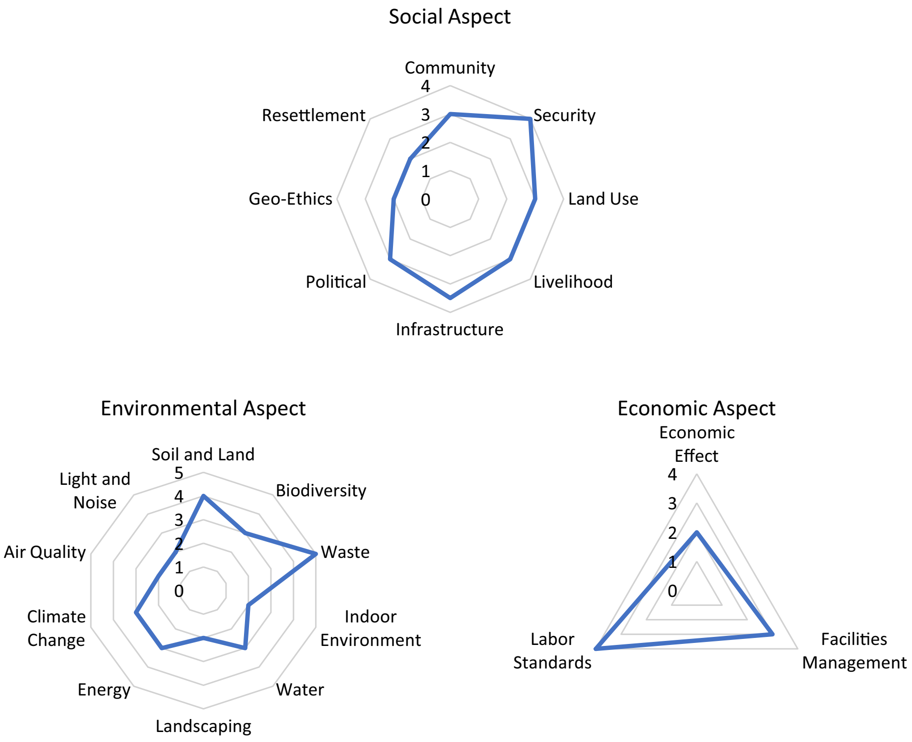


Fig. 11 Sample averaged Geo-SAT score

a detailed literature review of sustainability, geotechnology, past and current construction practices, recommendations of researchers as a way forward and the existing appraisal techniques, a new assessment tool called *Geo-SAT* (Geotechnical Sustainability Assessment Tool) was developed. The tool is based on 4 Es (engineering, equity, economy and environment) and dedicated to geotechnical projects. Using indicators and sub-indicators specific to geotechnical projects, Geo-SAT covers the “triple bottom line” approach. A reliable scale of 1 (detrimental) to 5 (significantly improved) was used that reflects the impact on sustainability. The scale is reliable as it is easy to comprehend and follow. Geo-SAT is developed using 169 indicators, 90 devoted to engineering, 31 to social characterized by 8 stages, 37 to environmental based on 10 stages and 11 to economic aspect assessed in 3 stages. The total number of indicators retained from Environmental Geotechnics Indicators is 24. A total score for each stage is calculated, averaged and plotted on a graph in the form of a closed polygon. The greater the area of the closed polygon, the more sustainable is the project. The different aspects are differentiated in this tool that helps in understanding sustainability related to geotechnical projects. The major strengths of *Geo-SAT* are:

- The indicators created are explicit to geotechnical projects.
- This tool gives the adaptability of including or barring indicators according to the nature of the project.
- The scale is well-characterized and straightforward.
- This system will go about as a code for guaranteeing sustainability in geotechnics.

- Geo-SAT targets the United Nations Sustainable Development Goals to achieve sustainable development agenda for 2030.
- The average score for each stage gives a clear reflection of performance at each stage and ultimately the respective aspect.
- Assessment can be carried out at any stage of the project. Iterative assessments will ensure continuous improvement along the timeline of the project, thus ensuring better project management.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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