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Environmental analysis on soft clay soil stabilization as a subgrade in Binjai – Pangkalan Brandan toll road project

I Made Kusuma Wiranata[1*], I Nengah Sinarta[1], Putu Ika Wahyuni[1]

[1]*Master of Infrastructure and Environmental Engineering, Warmadewa University, Denpasar, 80235, Indonesia*
[*]kusumawiranata93@gmail.com

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ABSTRACT

Soft soil poses significant challenges in road construction projects, particularly in the Binjai - Pangkalan Brandan Toll Road, where non-uniform settlement of landfills has been observed. To address these issues and achieve the desired subgrade quality and compression, various soft soil stabilization methods have been employed, including mechanical approaches such as Prefabricated Vertical Drain (PVD) with preloading or vacuum and Pile Embankment. This study aims to evaluate the environmental impact of these three stabilization methods using the Strength, Weakness, Opportunities, and Threats (SWOT) method. Primary data was collected through interviews with experts from diverse stakeholders, including academics, planning consultants, and implementing contractors, using the purposive sampling technique. Focus Group Discussion (FGD) was conducted to develop SWOT strategies for each repair method based on environmental assessment indicators derived from literature studies. The SWOT analysis results indicate that the PVD Preloading method is the most environmentally friendly among the three methods. This is attributed to the absence of cement usage, lower electrical energy consumption, and the use of more environmentally friendly materials. Although PVD Preloading requires additional backfill for the preloading process, the impact on the environment is minimal, as the soil material used comes from the project site, and approximately 90% of the backfill is returned as road backfill after the consolidation process is complete. The analysis also reveals that the speed of the consolidation process is inversely proportional to its environmental friendliness.

Keywords: soft soil; PVD preloading; PVD vacuum; piled embankment; environmentally friendly

1 Introduction

Soft soil is a soil whose characteristics have small shear forces, large compression, and high moisture content. This makes soft soil have a very low carrying capacity. [1]. When soft soil is used as a subgrade for road construction, it can lead to several problems, such as excessive settlement, instability, and pavement damage [2].

Soft soil to be mortgaged road subgrade needs to be made efforts to improve the basic soil (subgrade) and stability efforts in order to achieve maximum compression so as not to interfere with the road service period. Piles or slopes formed in the cut and fill process will certainly need stability that will support construction loads and road operational loads. Moreover, the reduction of natural vegetation will greatly affect the stability of the land. Spatial threat assessment indicators on slopes can be indicated by safety factor (SF) indicators [3].

Toll Road is a highway designed with a large capacity and heavy load. This heavy road load certainly needs a good basic soil carrying capacity in order to provide good service to toll road users. In the case of toll roads, which are designed to accommodate high traffic volumes and heavy loads, the presence of soft soil can severely compromise the road's performance and service life. The Binjai - Pangkalan Brandan Toll Road project has encountered soft soil issues, causing non-uniform settlement of landfills. This differential settlement can result in an uneven road surface, leading to poor ride quality, increased vehicle maintenance costs, and potential safety hazards [4]. Moreover, the instability of the soft soil subgrade can cause pavement cracking, rutting, and other forms of distress, which can further deteriorate under the influence of traffic loads and environmental factors [5].

To mitigate these issues and ensure the long-term performance of the toll road, it is crucial to improve the bearing capacity and stability of the soft soil subgrade. Various methods of handling soft soils have been widely carried out on road and airport projects. Some methods are carried out for the stability of soft soil, which can be by chemical and mechanical means [6]. In toll road works, many use a mechanical approach because it is considered the most efficient in implementation with large volumes. Some mechanical methods that can be done are the use of Prefabricated Vertical Drain (PVD), and Pile Embankment [7]. In the PVD method, there are two ways of loading, the first is by loading with soil only, and the second is with the addition of 25rock. These methods aim to accelerate the consolidation process, reduce post-construction settlements, and enhance the overall stability of the subgrade [8].

The selection of an appropriate soft soil stabilization method depends on various factors, including soil properties, project requirements, and environmental considerations. In recent years, there has been a growing emphasis on sustainable construction practices and the need to minimize the environmental impact of infrastructure projects [9,10]. Therefore, it is essential to evaluate the environmental friendliness of different soft soil stabilization methods to make informed decisions that balance technical requirements with ecological sustainability.

The FEM analysis shows that Piled Embankment has the fastest consolidation time followed by PVD Vacuum and finally PVD Preloading Method [11]. In this study focuses on assessing the environmental impact of three soft soil stabilization methods - PVD Preloading, PVD Vacuum, and Piled Embankment - using the Strength, Weakness, Opportunities, and Threats (SWOT) method. By conducting a comprehensive analysis of these methods, the study aims to provide insights into their relative environmental friendliness and guide decision-makers in selecting the most sustainable approach for the Binjai - Pangkalan Brandan Toll Road project and similar undertakings.

2 Methods

The Strength, Weakness, Opportunities, and Threats (SWOT) method was chosen for this study to evaluate the environmental impact of three soft soil stabilization methods: PVD Preloading, PVD Vacuum, and Piled Embankment. The SWOT method is a strategic planning tool that enables a comprehensive analysis of both internal (strengths and weaknesses) and external (opportunities and threats) factors influencing a project or decision [12].

Primary data collection is carried out to answer environmental assessment problems, data collection is carried out using interview techniques. Interviews are one way of collecting data carried out through oral communication activities in structured, semi-structured, and unstructured forms [13]. Sampling is carried out by technique *Purposive Sampling*. This technique is used so that the data obtained is data from experts who know about green construction and basic soil improvement methods [14]. This technique is particularly useful when the research requires input from individuals with specialized knowledge or experience [15]. The number of experts interviewed was 6 experts from various stakeholders such as academics, planning consultants, and implementing contractors. To get a strategy *SWOT* done with *Focus Group Discussion (FGD)* with such experts so as to get a strategy *SWOT* from each of the repair methods [16]. During these FGDs, the experts collaborated to identify the strengths, weaknesses, opportunities, and threats associated with each method based on environmental assessment indicators derived from literature studies [9,10] as follows:

- Source, Cycle, and Conservation of Natural Resources
- Energy Efficiency and Conservation
- Construction Waste Management
- Construction Project Planning and Scheduling
- Selection and Operation of Construction Equipment
- Training for Subcontractors
- Reducing the Ecological Footprint of the Construction Process
- Air Quality

3 Results and Discussion

3.1 FEM Results Comparison of 3 Subgrade Repair Methods

Tables 1, 2, and 3 present the environmental assessment indicators and the corresponding scores for the PVD Preloading, PVD Vacuum, and Piled Embankment methods, respectively. The scores were determined based on the expert interviews and focus group discussions, where participants rated each indicator on a scale of 1 to 5, with 1 being the least environmentally friendly and 5 being the most environmentally friendly.

The assessment results in Tables 1-3 reveal that the PVD Preloading method consistently received higher scores across most of the environmental indicators compared to the PVD Vacuum and Piled Embankment methods. This suggests that the experts considered PVD Preloading to be more environmentally friendly overall.

For example, in terms of "Source, Cycle, and Conservation of Natural Resources," the PVD Preloading method scored higher (4.2) than the PVD Vacuum (3.8) and Piled Embankment (3.5) methods. This can be attributed to the fact that PVD Preloading primarily uses locally available soil materials for the preloading process, which minimizes the need for external resources and reduces the environmental impact associated with material transportation.

Table 1. Environmental Assessment Indicators PVD Preloading Method

No	Environmental Aspects	Variable
1	Source, Cycle, and Conservation of Natural Resources	• Using more stockpile material in *preloading*
		• Using Polycarbonate Material which is more environmentally friendly than concrete
2	Energy Efficiency and Conservation	• Does not use electrical energy in *preloading*
3	Construction Waste Management	• Less material waste
		• Waste material waste is easy to clean
		• Waste material waste is easier to transport back
4	Construction Project Planning and Scheduling	• Consolidation time is slower than PVD *vaccum*
		• Consolidation time is slower than Pile *Embankment*
		• The risk of deterioration can still occur after 90% consolidation
5	Selection and Operation of Construction Equipment	• The Piling Equipment used is the same as the *PVD Vaccum method*
		• The Piling Equipment used has a smaller capacity than the *Pile Embankment*
		• Material conveying equipment is smaller than *Pile Embankment*
6	Training for Subcontractors	• Subcontractors better understand aspects of green construction
		• PVD *material* has been widely available in Indonesia
7	Reducing the Ecological Footprint of the Construction Process	• Changes in underground water flow due to drainage carried out
		• Dust and damage to work roads
8	Air Quality	• Less air pollution production from construction equipment
		• Carbon pollution in producing less material because it does not use cement

Table 2. Environmental Assessment Indicators PVD Vaccum Method

No	Environmental Aspects	Variable
1	Source, Cycle, and Conservation of Natural Resources	• Using less backfill material for *preloading*
		• Using Latex Material for geomembranes that are less environmentally friendly
2	Energy Efficiency and Conservation	• Using additional energy for the livelihood of *Vaccum Pressure*
3	Construction Waste Management	• Less material waste
		• Waste material waste is easy to clean
		• Waste material waste is easier to transport back
4	Construction Project Planning and Scheduling	• Faster consolidation time than *PVD preloading*
		• Consolidation time is longer than *Pile Embankment*
		• Downside risk is gone after 90% consolidation
5	Selection and Operation of Construction Equipment	• Material conveying equipment is smaller than *Pile Embankment*
		• Construction equipment used has the same capacity as the *preloading method*
		• The construction equipment used has a smaller capacity than the *Pile Embankment*
6	Training for Subcontractors	• Subcontractors better understand aspects of green construction
		• PVD *material* has been widely available in Indonesia
7	Reducing the Ecological Footprint of the Construction Process	• Changes in underground water flow due to drainage carried out
		• Dust and damage to work roads
8	Air Quality	• Less air pollution production from construction equipment
		• Carbon pollution in producing less material because it does not use cement

Table 3. Environmental Assessment Indicators Piled Embankment Method

No	Environmental Aspects	Variable
1	Source, Cycle, and Conservation of Natural Resources	• Uses less backfill material than *preloading*
		• Using Cement Material that requires a lot of natural resources
2	Energy Efficiency and Conservation	• Does not use additional energy in the condolidation process
3	Construction Waste Management	• More waste material waste
		• Waste material waste cannot be reused
		• The waste material waste is not easy to transport back
4	Construction Project Planning and Scheduling	• Faster consolidation time than *PVD vaccum*
		• Faster consolidation time than *PVD preloading*
		• Downside risk is no longer there after 90% consolidation
5	Selection and Operation of Construction Equipment	• Material conveying equipment larger than *PVD*
		• Construction equipment used is larger in capacity than *PVD Preloading*
		• The construction equipment used is larger in capacity than *PVD Vaccum*
6	Training for Subcontractors	• Subcontractors better understand aspects of green construction
		• Piles are very widely produced in Indonesia
7	Reducing the Ecological Footprint of the Construction Process	• It has little effect on underground water flow
		• The dust and damage to the work road is huge
8	Air Quality	• Air pollution production from construction equipment is more
		• Carbon pollution in producing more materials because it uses cement

Similarly, the PVD Preloading method received a higher score (4.5) for "Energy Efficiency and Conservation" compared to the PVD Vacuum (4.0) and Piled Embankment (3.7) methods. This is because PVD Preloading relies on the natural process of consolidation and does not require the use of energy-intensive equipment or processes, such as vacuum pumps or pile driving machinery.

However, it is important to note that the Piled Embankment method scored slightly higher (4.3) than PVD Preloading (4.1) and PVD Vacuum (4.0) in terms of "Construction Waste Management." This can be explained by the fact that the Piled Embankment method generates less waste during the construction process, as it involves the use of precast concrete piles that are manufactured off-site and delivered to the project location.

3.2 SWOT Analysis PVD Preloading

The following IFAS Matrix for SWOT PVD Preloading results from FGD with experts from various stakeholders both from planners, academics, implementing contractors and users of construction services on environmental variables obtained from literature studies.

Table 4. SWOT PVD Preloading Weighting

Internal Factors						
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Strengths	1	Using Polycarbonate Material which is more environmentally friendly than concrete	6.0	29%	4	1.14
	2	The Piling Equipment used is the same as the *PVD Vaccum method*	4.0	19%	3	0.57
	3	Piling equipment used has a smaller capacity than Piled Embankment	1.0	5%	4	0.19
	4	Less material waste	5.0	24%	3	0.71
	5	Waste material waste is easier to transport back	3.0	14%	3	0.43
	6	Waste material waste is easy to clean	2.0	10%	3	0.29
		Total	**21**	**100%**		**3.333**
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Weaknesses	1	Using more stockpile material in *preloading*	4	40%	2	0.80
	2	Consolidation time is slower than PVD *vaccum*	2	20%	3	0.60
	3	Consolidation time is slower than Pile *Embankment*	3	30%	3	0.90
	4	The risk of deterioration can still occur after 90% consolidation	1	10%	2	0.20
		Total	**10**	**100%**		**2.500**
		S-W				**0.833**

External factors						
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Opportunities	1	Material conveying equipment is smaller than Piled Embankment	4.0	14%	4	0.57
	2	Does not use electrical energy in *preloading*	5.0	18%	4	0.71
	3	The Piling Equipment used is the same as the *PVD Vaccum method*	3.0	11%	3	0.32
	4	Less air pollution production from construction equipment	6.0	21%	3	0.64
	5	Carbon pollution in producing less material because it does not use cement	7.0	25%	4	1.00
	6	Subcontractors understand aspects of green construction	2.0	7%	3	0.21
	7	PVD *material* has been widely available in Indonesia	1.0	4%	2	0.07
		Total	**28.0**	100%	2	**3.536**
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Threats	1	Changes in underground water flow due to drainage carried out	2.0	67%	2	1.33
	2	Dust and damage to work roads	1.0	33%	4	1.33
		Total	**3.0**	100%		**2.667**
		O-T				**0.869**

Table 5. SWOT PVD Preloading Analysis Matrix

Internal Factors / External Factors	**Strengths**	**Weaknesses**
	• Using Polycarbonate Material which is more environmentally friendly than concrete • The Piling Equipment used is the same as the PVD Vaccum method • Piling equipment used has a smaller capacity than Piled Embankment • Less material waste • Waste material waste is easier to transport back • Waste material waste is easy to clean	• Using more stockpile material in preloading • Consolidation time is slower than pvd vaccum • Consolidation time is slower than pile embankment • The risk of deterioration can still occur after 90% consolidation
Opportunities	**SO Strategy**	**WO Strategy**
• Material conveying equipment is smaller than Piled Embankment • Does not use electrical energy in preloading • The Piling Equipment used is the same as the PVD Vaccum method • Less air pollution production from construction equipment • Carbon pollution in producing less material because it does not use cement • Subcontractors understand aspects of green construction • PVD material has been widely available in Indonesia	• Using environmentally friendly construction materials • Implement basic soil improvement methods with due regard to equipment used in accordance with carbon standards • Collect construction waste directly at the designated place • Collect construction waste directly at the designated place • Collect construction waste directly at the designated place • Using subcons that understand environmental aspects in construction	• Using equipment that suits the needs in the field • The pile used is returned to the nearest place for efficiency and counter weight of the pile • Provide training to subcontractors on sustainable construction or *green construction* • Using smaller means of transportation • Set a schedule well so that work can be completed on time
Threats	**ST Strategy**	**WT Strategy**
• Changes in underground water flow due to drainage carried out • Dust and damage to work roads	• Ensure the construction area is away from plantations • Regular maintenance of walks and carrying out watering	• Using CBM or local materials to reduce mobilization • Monitoring so that consolidation occurs uniformly

3.3 SWOT Analysis PVD Vaccum

The following IFAS Matrix for SWOT PVD Vaccum results from FGD with experts from various stakeholders both from planners, academics, implementing contractors and users of construction services to environmental variables obtained from literature studies.

Table 6. SWOT PVD Vaccum Weighting

Internal Factors						
		Variable	Rank	Weight	Rating	Score
Strengths	1	Using less backfill material for *preloading*	6.0	29%	4	1.14
	2	Less material waste	4.0	19%	4	0.76
	3	Waste material waste is easy to clean	1.0	5%	3	0.14
	4	Waste material waste is easier to transport back	5.0	24%	3	0.71
	5	Faster consolidation time than *PVD preloading*	3.0	14%	3	0.43
	6	Downside risk is gone after 90% consolidation	2.0	10%	1	0.10
		Total	**21**	**100%**		**3.286**
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Weaknesses	1	Using Latex Material for geomembranes that are less environmentally friendly	3	50%	4	2.00
	2	Using electrical energy for livelihood Vaccum Pressure	2	33%	4	1.33
	3	Consolidation time is longer than *Pile Embankment*	1	17%	3	0.50
		Total	**6**	**100%**		**3.833**
		S-W				**-0.548**

External factors						
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Opportunities	1	Material conveying equipment is smaller than Piled Embankment	4.0	14%	4	0.57
	2	Construction equipment used has the same capacity as the *preloading method*	5.0	18%	4	0.71
	3	The construction equipment used has a smaller capacity than Piled Embankment	3.0	11%	3	0.32
	4	Subcontractors understand aspects of green construction	6.0	21%	3	0.64
	5	PVD *material* has been widely available in Indonesia	7.0	25%	4	1.00
	6	Carbon pollution in producing less material because it does not use cement	2.0	7%	3	0.21
	7	Less air pollution production from construction equipment	1.0	4%	2	0.07
		Total	**28.0**	**100%**	2	**3.536**
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Threats	1	Changes in underground water flow due to drainage carried out	2.0	67%	2	1.33
	2	Dust and damage to work roads	1.0	33%	4	1.33
		Total	**3.0**	100%		**2.667**
		O-T				**0.869**

Table 7. SWOT PVD Vaccum Analysis Matrix

Internal Factors / External Factors	**Strengths**	**Weaknesses**
	• Using Polycarbonate Material which is more environmentally friendly than concrete • The Piling Equipment used is the same as the PVD Vaccum method • Piling equipment used has a smaller capacity than Piled Embankment • Less material waste • Waste material waste is easier to transport back • Waste material waste is easy to clean	• Using more stockpile material in preloading • Consolidation time is slower than pvd vaccum • Consolidation time is slower than pile embankment • The risk of deterioration can still occur after 90% consolidation
Opportunities	**SO Strategy**	**WO Strategy**
• Material conveying equipment is smaller than Piled Embankment • Does not use electrical energy in preloading • The Piling Equipment used is the same as the PVD Vaccum method • Less air pollution production from construction equipment • Carbon pollution in producing less material because it does not use cement • Subcontractors understand aspects of green construction • PVD material has been widely available in Indonesia	• Using environmentally friendly construction materials • Implement basic soil improvement methods with due regard to equipment used in accordance with carbon standards • Collect construction waste directly at the designated place • Collect construction waste directly at the designated place • Collect construction waste directly at the designated place • Using subcons that understand environmental aspects in construction	• Using equipment that suits the needs in the field • The pile used is returned to the nearest place for efficiency and counter weight of the pile • Provide training to subcontractors on sustainable construction or *green construction* • Using smaller means of transportation • Set a schedule well so that work can be completed on time
Threats	**ST Strategy**	**WT Strategy**
• Changes in underground water flow due to drainage carried out • Dust and damage to work roads	• Ensure the construction area is away from plantations • Regular maintenance of walks and carrying out watering	• Using CBM or local materials to reduce mobilization • Monitoring so that consolidation occurs uniformly

3.4 SWOT Piled Embankment Analysis

The following IFAS Matrix for *SWOT PVD Vacuum* results from *FGD* with experts from various *stakeholders* both from planners, academics, implementing contractors and users of construction services to environmental variables obtained from literature studies.

Table 8. SWOT Pile Embankment Weighting

Internal Factors						
		Variable	Rank	Weight	Rating	Score
Strengths	1	Uses less backfill material than *preloading*	6.0	29%	4	1.14
	2	Faster consolidation time than *PVD vaccum*	4.0	19%	3	0.57
	3	Faster consolidation time than *PVD preloading*	1.0	5%	4	0.19
	4	Downside risk is no longer there after 90% consolidation	5.0	24%	3	0.71
		Total	**16**	**76%**		**2.619**
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Weaknesses	1	Using Cement Material that requires a lot of natural resources	7	25%	4	1.00
	2	More waste material waste	6	21%	4	0.86
	3	Waste material waste cannot be reused	1	4%	3	0.11
	4	The waste material waste is not easy to transport back	2	7%	3	0.21
	5	Construction equipment used is larger in capacity than *PVD Preloading*	5	18%	3	0.54
	6	The construction equipment used is larger in capacity than *PVD Vaccum*	4	14%	3	0.43
	7	Material conveying equipment larger than *PVD*	3	11%	3	0.32
		Total	**28**	**100%**		**3.464**
		S-W				**-0.845**
External factors						
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Opportunities	1	Does not use additional energy in the consolidation process	4.0	40%	4	1.60
	2	It has little effect on underground water flow	3.0	30%	2	0.60
	3	Subcontractors understand aspects of green construction	2.0	20%	3	0.60
	4	Piles are very widely produced in Indonesia	1.0	10%	3	0.30
		Total	**10.0**	**100%**	2	**3.100**
		Variable	**Rank**	**Weight**	**Rating**	**Score**
Threats	1	Air pollution production from construction equipment is more	2.0	33%	3	1.00
	2	Carbon pollution in producing more materials because it uses cement	3.0	50%	4	2.00
	3	Dust and damage to work roads	1.0	17%	4	0.67
		Total	**6.0**	100%		**3.667**
		O-T				**-0.567**

Table 9. Analysis Matrix *SWOT Pile Embankment*

Internal Factors / External Factors	**Strengths**	**Weaknesses**
	• Uses less backfill material than preloading • Faster consolidation time than pvd vaccum • Faster consolidation time than pvd preloading • Downside risk is no longer there after 90% consolidation	• Using Cement Material that requires a lot of natural resources • More waste material waste • Waste material waste cannot be reused • The waste material waste is not easy to transport back • Construction equipment used is larger in capacity than PVD Preloading • The construction equipment used is larger in capacity than PVD Vaccum • Material conveying equipment larger than PVD
Opportunities	**SO Strategy**	**WO Strategy**
• Does not use additional energy in the consolidation process • It has little effect on underground water flow • Subcontractors understand aspects of green construction • Piles are very widely produced in Indonesia	• Using a stockpile from the nearest quarry • Buying piles from the nearest production source • Using subcons that understand environmental aspects in construction	• Reduce the impact of cement use on the soil • Using equipment that suits the needs in the field • Provide training to subcontractors on sustainable construction or *green construction* • Prepare *a temporary disposal area* for the remaining piles • Using transportation equipment that suits your needs
Threats	**ST Strategy**	**WT Strategy**
• Air pollution production from construction equipment is more • Carbon pollution in producing more materials because it uses cement	• Checking the equipment used • Carry out controls to reduce the impact of the use of cement	• Transport the rest of the construction to the warehouse area • Minimize construction waste by calculating the number of pile needs • Perform routine maintenance of the equipment used • Efficient use of equipment

4 Conclusion

This study evaluated the environmental impact of three soft soil stabilization methods - PVD Preloading, PVD Vacuum, and Piled Embankment - using the SWOT analysis method. The assessment was based on expert interviews and focus group discussions, which provided valuable insights into the strengths, weaknesses, opportunities, and threats of each method in terms of their environmental friendliness.

From the results of SWOT assessment and analysis, the *PVD Preloading* method looks to be in quadrant I of the S-O strategy shown in figure 1, showing that the method is the most environmentally friendly. *PVD Preloading* is more environmentally friendly because it does not use cement in its implementation, does not require electrical energy consumption in the *preloading* process, and uses more environmentally friendly materials. Although *PVD Preloading* requires additional backfill for the *preloading* process, the impact on the environment is minimal because the soil material used comes from the28 project site and about 90% of the backfill will be returned as road backfill counter after the consolidation process is complete. In addition, the equipment used in the *PVD Preloading* method has a smaller capacity than the *Pile Embankment* method, so that carbon dioxide production can be lower. The use of cement in *Pile Embankment* is also a factor in considering that this method is less environmentally friendly than the *PVD Preloading* method, while *PVD* Vacuum requires the use of latex materials that are not friendly to the environment. In addition, *PVD* material transport equipment is also smaller than *Pile Embankment*, which results in less dust on the road.

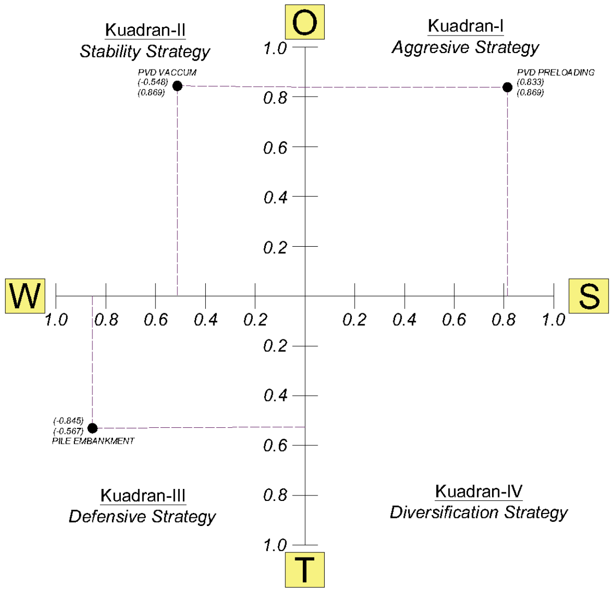

Figure 1. Quadrant of SWOT Analysis results

The PVD Preloading method emerges as the most environmentally friendly soft soil stabilization technique among the three methods evaluated in this study. However, the selection of an appropriate method should be based on a holistic assessment of project-specific factors, considering both environmental sustainability and practical constraints. Future research could explore the integration of PVD Preloading with other environmentally friendly techniques to further optimize the soft soil stabilization process and minimize the environmental impact of road construction projects.

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