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Analisis Identifikasi Bahaya dan Penilaian Risiko dalam Menentukan Tingkat Risiko pada Pekerjaan Perbaikan Tanah dengan Metode *Vacuum Consolidation*

Deano Alvaro Binnendijk, Rossy Armyn Machfudiyanto
Departemen Teknik Sipil dan Lingkungan, Fakultas Teknik, Universitas Indonesia, Depok 16424, Indonesia

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***Correspondence email:**
binnendijkdeano@gmail.com, rossy.armynm@gmail.com

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ABSTRAK

Metode Vacuum Consolidation merupakan salah satu teknik perbaikan tanah lunak yang efektif; namun, implementasinya melibatkan penggunaan alat berat, instrumen bertekanan tinggi, dan lingkungan kerja geoteknik yang kompleks, yang dapat menimbulkan berbagai bahaya Kesehatan dan Keselamatan Kerja (K3). Studi ini bertujuan untuk mengidentifikasi potensi bahaya, menilai tingkat risiko, dan merumuskan langkah-langkah pengendalian untuk pekerjaan perbaikan tanah menggunakan metode Konsolidasi Vakum. Analisis dilakukan menggunakan pendekatan Identifikasi Bahaya dan Penilaian Risiko (IBPRP) berdasarkan matriks penilaian risiko standar. Data dikumpulkan melalui observasi lapangan dan tinjauan literatur. Hasil identifikasi bahaya mengungkapkan beberapa insiden potensial kritis, termasuk rig hidrolik Prefabricated Vertical Drain (PVD) yang tidak stabil yang dapat terbalik di tanah lunak, pekerja yang bersentuhan dengan kabel listrik hidup yang tidak terisolasi, dan kontak dengan pompa atau panel kontrol listrik yang dapat mengakibatkan sengatan listrik fatal. Penilaian risiko awal mengklasifikasikan bahaya yang teridentifikasi ke dalam kategori risiko rendah, sedang, tinggi, dan ekstrem. Melalui penerapan langkah-langkah mitigasi yang mencakup pengendalian teknik, pengendalian administratif, dan kepatuhan ketat terhadap persyaratan Alat Pelindung Diri (APD), tingkat risiko residual diproyeksikan akan berkurang hingga tingkat yang dapat diterima. Studi ini diharapkan dapat berfungsi sebagai pedoman untuk penerapan Sistem Manajemen Kesehatan dan Keselamatan Kerja pada proyek geoteknik serupa untuk meminimalkan kecelakaan kerja dan mengoptimalkan produktivitas proyek.

Keywords:
Hazard Identification, Risk Assessment, Vacuum Consolidation, Occupational Health and Safety (OHS).

ABSTRACT

Vacuum Consolidation is one of the effective soft soil improvement techniques; however, its implementation involves the use of heavy equipment, high-pressure instruments, and complex geotechnical working environments, which may generate various Occupational Health and Safety (OHS) hazards. This study aims to identify potential hazards, assess risk levels, and formulate control measures for soil improvement works using the Vacuum Consolidation method. The analysis was conducted using the Hazard Identification and Risk Assessment (HIRA) approach based on a standard risk assessment matrix. Data were collected through field observations and literature reviews. The hazard identification results revealed several critical potential incidents, including unstable Prefabricated Vertical Drain (PVD) hydraulic rigs that may overturn on soft ground, workers coming into contact with uninsulated live electrical cables, and unauthorized contact with pumps or electrical control panels that may result in fatal electric shock. The initial risk assessment classified the identified hazards into low, medium, high, and extreme risk categories. Through the implementation of mitigation measures encompassing engineering controls, administrative controls, and strict compliance with Personal Protective Equipment (PPE) requirements, the residual risk level is projected to be reduced to an acceptable level. This study is expected to serve as a guideline for the implementation of Occupational Health and Safety Management Systems in similar geotechnical projects to minimize workplace accidents and optimize project productivity.

INTRODUCTION

Infrastructure development in Indonesia continues to increase in response to the growing demand for toll roads, seaports, industrial estates, airports, and other public facilities. Many of these construction projects are carried out on soft soil deposits characterized by low bearing capacity, high compressibility, and significant settlement potential. Such conditions may hinder construction activities and lead to geotechnical problems if appropriate ground improvement measures are not implemented prior to construction (Das, 2019). Therefore, ground improvement techniques play a critical role in enhancing soil properties and ensuring the stability and safety of infrastructure development.

One of the most widely applied ground improvement techniques for soft soil is *vacuum consolidation*. This method utilizes vacuum pressure to induce consolidation and accelerate pore water dissipation without requiring large surcharge embankments. Compared with conventional preloading methods, vacuum consolidation offers several advantages, including shorter construction time, improved consolidation efficiency, and more uniform settlement performance (Chu et al., 2000; Indraratna et al., 2015; Indraratna et al., 2005). Owing to these advantages, the method has been successfully implemented in numerous infrastructure projects involving soft ground conditions.

Despite its technical benefits, the implementation of *vacuum consolidation* involves a variety of work activities that may expose workers to occupational hazards. The installation of *Prefabricated Vertical Drains* (PVDs), operation of hydraulic rigs, vacuum pumping systems, and associated supporting equipment require intensive interaction between workers, machinery, materials, and challenging ground conditions (Indraratna et al., 2015; Indraratna et al., 2005). During these activities, workers may be exposed to hazards such as struck-by incidents, caught-in or caught-between accidents, slips and falls on muddy surfaces, electrical hazards, and equipment overturning due to insufficient soil bearing capacity (Hinze, 2006; Ramli, 2013). These hazards have the potential to cause serious injuries, fatalities, equipment damage, and project delays.

Accidents involving heavy equipment remain one of the major safety concerns in construction and ground improvement projects. In soft soil environments, inadequate risk control measures may increase the likelihood of rig instability, equipment overturning, and other operational failures. Such incidents not only result in economic losses and equipment damage but may also significantly affect worker safety and project performance (Goetsch, 2019; Hinze, 2006). Consequently, effective occupational health and safety management is essential throughout all stages of vacuum consolidation activities to minimize risks and ensure safe project execution (ISO, 2018b; Latief et al., 2017a; Latief et al., 2017b; Machfudiyanto et al., 2021; Machfudiyanto et al., 2017).

In construction projects, the *Hazard Identification and Risk Assessment* (HIRA) approach is widely recognized as an effective tool for identifying workplace hazards and evaluating associated risks. Hazard identification aims to recognize all potential sources of danger present in work activities, while risk assessment evaluates the likelihood and severity of adverse events in order to determine the level of risk. The results of the assessment provide a basis for prioritizing risk control measures and allocating resources to address critical hazards (ISO, 2018a; Ramli, 2010). This approach is consistent with the principles of risk management outlined in ISO 31000 and the occupational health and safety management requirements specified in ISO 45001, both of which emphasize systematic hazard identification, risk evaluation, and continuous improvement (ISO, 2018a; ISO, 2018b).

The application of HIRA is particularly important in *vacuum consolidation* projects because of the complexity of activities involving heavy equipment operations, soft soil conditions, vacuum systems, and dynamic construction environments. Through a systematic assessment process, potential hazards can be identified at each stage of the work process, enabling organizations to implement appropriate engineering controls, administrative controls, and personal protective measures in accordance with the hierarchy of controls (Kementerian PUPR, 2021; Ramli, 2013; Sousa et al., 2014).

Previous studies have extensively examined the geotechnical performance and effectiveness of *vacuum consolidation* in accelerating the consolidation of soft soils (Chu et al., 2000; Indraratna et al., 2015; Indraratna et al., 2005; Ramli, 2013). However, studies focusing specifically on occupational hazard identification and risk assessment during *vacuum consolidation* operations remain limited. Most existing research emphasizes technical and geotechnical aspects, whereas the safety risks associated with equipment operation, worker exposure, and construction activities have received relatively little attention. Considering the unique characteristics of *vacuum consolidation* projects, a comprehensive evaluation of occupational hazards and risks is necessary to support safer project implementation.

Therefore, this study aims to analyze hazard identification and risk assessment in ground improvement projects using the *vacuum consolidation* method. The study identifies potential hazards associated with each stage of the work process, evaluates risk levels using a risk assessment matrix, and proposes appropriate control measures to reduce identified risks. The findings are expected to provide practical guidance for construction companies in improving occupational health and safety performance, reducing workplace accidents, and supporting the successful implementation of ground improvement projects in a safe, effective, and sustainable manner.

Theory

Hazard Identification and Risk Assessment (HIRA)

Following the collection and validation of primary data, the next step involved calculating risk values and determining risk levels based on the methodology stipulated in relevant regulations. The identified risks encompassed various factors that could affect the execution of ground improvement works, including both technical and managerial aspects. Risk levels were determined using the approach established in the Regulation of the Ministry of Public Works and Housing (Permen PUPR) No. 10 of 2021, which classifies risks into three categories: low risk, medium risk, and high risk. This classification is based on two primary parameters, namely the probability of occurrence and the severity of consequences. The risk level was calculated using the following equation:

$$F \times D = R \quad (1)$$

Where:
R = Risk level
F = Frequency (probability of occurrence)
D = Severity of impact (consequence)

After the risk value was calculated, the results were analyzed and plotted using the risk matrix provided in Permen PUPR No. 10 of 2021. The risk matrix offers a visual representation of risk distribution based on the combination of probability and severity values. Through this matrix, risks can be prioritized systematically, enabling the development of appropriate mitigation measures and control strategies. Risks classified as high require immediate corrective actions, whereas medium and low risks may be managed through preventive and monitoring measures in accordance with the established risk management framework.

The HIRA process in this study consisted of three main stages: hazard identification, risk assessment, and risk control recommendation. Hazard identification was conducted for each activity involved in the vacuum consolidation process, including material mobilization, PVD installation, vacuum system operation, and supporting construction activities. Subsequently, the identified hazards were assessed to determine their risk levels based on frequency and severity criteria. Finally, appropriate control measures were proposed in accordance with the hierarchy of controls, including engineering controls, administrative controls, and the use of personal protective equipment (PPE), with the objective of reducing residual risks to an acceptable level.

	Keparahan				
Kekerapan	**1**	**2**	**3**	**4**	**5**
1	1	2	3	4	5
2	2	4	6	8	10
3	3	6	9	12	15
4	4	8	12	16	20
5	5	10	15	20	25

Keterangan
1-4 : Tingkat risiko kecil
5-12 : Tingkat risiko sedang
15-25 : Tingkat risiko besar

Figure 1. Risk Assessment Matrix
Source: Adapted from Regulation of the Ministry of Public Works and Housing of the Republic of Indonesia No. 10 of 2021 concerning the Construction Safety Management System.

Construction Safety Performance

The Construction Safety Plan (Rencana Keselamatan Konstruksi—RKK) is a document developed as part of the Construction Safety Management System (CSMS) to ensure that all potential hazards and risks arising during construction activities are systematically identified, assessed, and controlled. The RKK serves as a guideline for implementing construction safety practices, including hazard identification, risk assessment, determination of control measures, and emergency response procedures for each stage of construction work. In Indonesia, the preparation and implementation of the RKK are mandated under the Regulation of the Ministry of Public Works and Housing of the Republic of Indonesia No. 10 of 2021 concerning the Construction Safety Management System (CSMS) (Kementerian PUPR, 2021).

The development of the RKK is based on risk management principles that integrate safety into both the planning and execution phases of construction projects. According to ISO 31000:2018, the risk management process consists of risk identification, risk analysis, risk evaluation, and the implementation of appropriate control measures aimed at minimizing adverse impacts on organizations and projects (ISO, 2018a). Similarly, ISO 45001:2018 emphasizes the importance of a risk-based approach within occupational health and safety management systems to prevent workplace accidents and continuously improve safety performance (ISO, 2018b; Latief et al., 2017a; Latief et al., 2017b; Machfudiyanto & Latief, 2017; Machfudiyanto et al., 2017).

In ground improvement projects utilizing the *vacuum consolidation* method, the RKK plays a crucial role due to the nature of the work, which involves heavy equipment operations, vacuum systems, and soft soil conditions that may generate various occupational safety risks. These risks include vacuum system failures, membrane leakage, ground instability, accidents involving heavy equipment, and hazards associated with the installation of *Prefabricated Vertical Drains* (PVDs) (Indraratna et al., 2015; Indraratna et al., 2005). Therefore, the RKK must adequately address these potential risks through comprehensive planning and the implementation of appropriate control measures tailored to site-specific conditions.

The implementation of the RKK is supported by various safety control instruments, including the preparation of Job Safety Analysis (JSA), the application of Standard Operating Procedures (SOPs), the use of Personal Protective Equipment (PPE), safety training programs, routine inspections, and continuous supervision of construction activities (Goetsch, 2019; Ramli, 2013; Tarwaka, 2017). Through a systematic and risk-based implementation of the RKK, workplace accidents can be minimized, thereby ensuring worker safety, maintaining project continuity, and supporting the successful completion of construction works. Consequently, effective construction safety performance serves as an important indicator of the overall success of construction project management (ISO, 2018b; Kementerian PUPR, 2021).

METHOD

This study was conducted to identify hazards and assess occupational risks associated with ground improvement works using the *vacuum consolidation* method. The research employed the *Hazard Identification and Risk Assessment* (HIRA) approach and followed applicable regulations, particularly the Regulation of the Ministry of Public Works and Housing of the Republic of Indonesia No. 10 of 2021 concerning the Construction Safety Management System (CSMS). Risk assessment and risk control evaluation were performed using both qualitative and quantitative approaches.

The HIRA implementation consisted of three main stages: hazard identification, risk assessment using a risk matrix, and risk control determination. Hazard identification was carried out for each activity involved in the *vacuum consolidation* process to identify potential sources of danger that could affect worker safety and project execution. Subsequently, the identified hazards were evaluated using a risk matrix based on the likelihood of occurrence and the severity of consequences. Finally, appropriate risk control measures were proposed to reduce the identified risks to an acceptable level.

Primary data were collected through field observations, site surveys, and questionnaires. The observations were conducted directly at the project site to identify work activities, operational conditions, and potential hazards associated with *vacuum consolidation* operations. Questionnaires were distributed to obtain expert judgments regarding the probability and severity of identified hazards.

To ensure the validity of the assessment, expert validation was conducted involving five specialists in the geotechnical field. The selected experts met the following criteria: (1) a minimum of five years of professional experience in geotechnical engineering or ground improvement projects; (2) possession of professional certification in construction management or geotechnical engineering; and (3) a recognized professional reputation within their respective fields. The experts were responsible for validating the identified hazards, risk assessments, and proposed control measures. In addition, relevant literature, standards, regulations, and previous studies were reviewed to support the hazard identification and risk assessment process.

Following the validation process, each identified hazard was assigned a likelihood score and a severity score based on the risk assessment criteria specified in Permen PUPR No. 10 of 2021. The risk value was calculated by multiplying the likelihood and severity scores. The resulting risk values were then plotted into a risk matrix to determine their respective risk categories. Based on the matrix classification, risks were categorized into low, medium, and high-risk levels. This classification enabled the prioritization of mitigation measures and the development of appropriate risk control strategies for each identified hazard.

The validated hazard data were subsequently analyzed using the risk classification criteria specified in Permen PUPR No. 10 of 2021 to determine the corresponding risk levels and prioritize control measures. The analysis results were used to formulate recommendations for engineering controls, administrative controls, and the use of personal protective equipment (PPE) in accordance with the hierarchy of controls. The ultimate objective was to reduce residual risks to an acceptable level and improve occupational safety performance during the implementation of *vacuum consolidation* works

RESULT

Hazard Identification and Risk Assessment

The initial stage of the *Hazard Identification and Risk Assessment* (HIRA) process involved systematically identifying hazards and associated risks for each work activity undertaken in the ground improvement project using the *vacuum consolidation* method. Hazard identification was conducted sequentially based on the workflow and operational stages of the project to ensure that all potential sources of risk were comprehensively evaluated.

The project was divided into nine major work packages, namely: (1) Soil Investigation, (2) Working Platform Construction and Joint Survey, (3) Vertical Drain Installation, (4) Horizontal Drain and Pipeline Network Installation, (5) Separated Tank and Main Tank Installation, (6) Installation of Monitoring Instrumentation, (7) Protective Layer

Installation, (8) Impermeable Membrane Installation, and (9) Vacuum Pump and Power Generator Installation. Across these work packages, a total of 32 work activities were identified and analyzed.

The hazard identification process resulted in the identification of 112 potential hazards and associated risks with varying levels of severity and likelihood across the different activities. These hazards included mechanical hazards related to heavy equipment operations, electrical hazards, ergonomic hazards, slip, trip, and fall hazards, struck-by and caught-between incidents, as well as risks associated with working on soft ground conditions. Each identified hazard was subsequently assessed using the established risk assessment criteria to determine its corresponding risk level and to establish appropriate control measures.

The results of the hazard identification process indicate that activities involving heavy equipment operations, PVD installation, vacuum system installation, and electrical equipment operation contributed the largest proportion of identified hazards. This finding highlights the importance of implementing effective risk control measures throughout the *vacuum consolidation* process to ensure worker safety and maintain project performance.

Risk Assessment Using the Risk Matrix

After the hazard identification process has been completed, the next step is to assess the risks by multiplying the frequency value by the severity value. The resulting risk value is then used to determine the risk level using a risk matrix. The frequency and severity values were obtained from questionnaires that had been validated by experts. Risk assessment using the risk matrix was conducted by multiplying the frequency score by the severity score.

Risk Ranking

Following the risk assessment process through the multiplication of frequency and severity values, the next step was to determine the risk ranking (risk level) for each identified hazard. Risk ranking was used to classify the level of risk based on the values obtained from the risk matrix, thereby identifying the priority of control and mitigation measures required. The higher the risk value, the higher the priority for implementing appropriate control measures.

In this study, risk ranking was determined using a 5×5 risk matrix that classified risks into several categories, namely low risk, medium risk, and high risk. The risk ranking results indicated that the risk levels associated with vacuum consolidation ground improvement works varied across different work activities. Activities involving heavy equipment operations, lifting activities, Prefabricated Vertical Drain (PVD) installation, and work performed on soft ground conditions tended to have higher risk levels compared to other activities. Through the risk ranking process, control priorities for each activity could be established, enabling risk mitigation measures to be implemented more effectively and systematically to support a safe working environment during the execution of vacuum consolidation works.

Table 1. Risk Ranking

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	PVD Piling	Equipment	PVD (hydraulic rig) equipment is unstable on soft ground	Heavy equipment overturned	15	High
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Separated & main tank installation	Equipment	Use of grinder, cutting torch, or welding without protection	Burns	15	High
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Worker	Worker touches live cable without insulation	Fatal electric shock	15	High
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Pump Running	Worker	Worker touches pump or electrical panel without permission	Fatal electric shock	15	High
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Pump Running	Environment	Exhaust gas from the generator	Air pollution	12	Medium
Vacuum	Installation of	Pump Running	Environment	Fuel or oil spills	Soil/water pollution	12	Medium

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
consolidation in road infrastructure project	Vacuum Pump and Electric Generator						
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Worker	Worker standing too close to the load being lifted	Crushed by a load if the sling breaks or the load shifts	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Equipment	Piling rig was not inspected before use	Heavy equipment overturned	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Equipment	Sling, shackle, or wire rope is worn, rusty, or does not meet load capacity.	Breaks off when lifting	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Equipment	Machine positioning error	Piling rig overturned	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Material	The load moves or swings when lifted	Hitting workers or Equipment in the area	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Material	The load (rig component) is unbalanced or not properly attached.	Tilting load, falling	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Environment	Soft, uneven, or muddy ground surface	Heavy equipment can tilt and overturned	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	rig equipment settings	Equipment	The rig equipment is unstable when erected	Rig tilted or fallen	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	rig equipment settings	Environment	The ground surface is uneven, soft, or muddy	Rig overturned	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	PVD Piling	Environment	Soft, muddy, and uneven ground	Heavy equipment slips	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	Mobilization of PHD materials & pipelines	Worker	Workers are near heavy equipment	Worker hit by vehicle or heavy equipment	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	Mobilization of PHD materials & pipelines	Equipment	Heavy equipment parked on uneven/soft ground	Risk of overturning	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Mobilization of heavy equipment & separated materials, main tank	Worker	Workers walk in heavy equipment traffic areas	Risk of being hit by a vehicle	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Excavation for Separated & main tank installation	Equipment	Heavy equipment operating without a certified operator	Heavy equipment damage	10	Medium

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Vibrating Wire Piezometer Installation	Worker	Pinched or crushed when lowering the sensor into the borehole	Worker slips or falls	10	Medium
Vacuum consolidation in road infrastructure project	Anchor Excavation	Anchor Excavation	Worker	Workers do not understand excavation evacuation procedures	Left in danger area during landslide	10	Medium
Vacuum consolidation in road infrastructure project	Anchor Excavation	Anchor Excavation	Equipment	Heavy equipment is unstable on soft ground	Heavy equipment overturned	10	Medium
Vacuum consolidation in road infrastructure project	Anchor Excavation	Embankment construction	Equipment	Heavy equipment overturned due to loose ground	Injury to operator	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Mobilization of vacuum pump materials & electric generators	Worker	Don't understand the safe zone of the lifting area	Enter the danger area while the equipment is operating	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Mobilization of vacuum pump materials & electric generators	Equipment	Sling, shackle, or wire rope is worn out / not suitable for capacity	Disconnected during removal	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Equipment	Generator without grounding	Fatal electric shock	10	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Environment	Muddy/damp work area	Electric shock due to current leakage	10	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Mobilization of PVD materials	Material	Loose material straps during transportation	Material falls from vehicle	9	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	PVD Piling	Material	PVD stuck in equipment during pile driving	Torn material	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	Mobilization of PHD materials & pipelines	Worker	Lack of focus due to fatigue	Error during binding material	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	Mobilization of PHD materials & pipelines	Material	Wet or slippery material	Risk of slipping when held	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	Mobilization of PHD materials & pipelines	Material	PHD (drainage core) is made of sharp plastic	Cut wound on hand while lifting	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	PHD Installation	Worker	Non-ergonomic working position when pulling or connecting PHD	Back injury	9	Medium
Vacuum consolidation in road infrastructure	Installation of Horizontal Drains and Pipe Networks	PHD Installation	Worker	Not using PPE	Hands exposed to hand equipments (cutters, scissors)	9	Medium

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
project							
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	PHD Installation	Material	PHD material is slippery when wet	Slipped or fell off the handle	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Mobilization of heavy equipment & separated materials, main tank	Material	Sharp materials (pipes, tank corners) are not protected	Cuts or tears in the skin	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Excavation for Separated & main tank installation	Material	Excavated soil piles up at the edge of the hole	Adding load on the side of the excavation, causing landslides	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Instrumentation coordinate stakeout	Worker	Non-ergonomic working position	Back injury	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Instrumentation coordinate stakeout	Material	Scratched wooden pegs marking coordinates	Cut wound on hand	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Vibrating Wire Piezometer Installation	Equipment	Drilling machine (hand auger/mechanical drill) injures worker (bounces, gets stuck)	Cut wound on hand	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Extensometer Installation	Worker	Drilling machine (hand auger/mechanical drill) injures workers (bounces, gets stuck)	Injured hand	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Extensometer Installation	Material	Exposure to grout/cement/bentonite (skin, eye, and respiratory irritation)	Skin or respiratory irritation	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Settlement Plate Installation	Worker	Pinched or crushed by material during installation of plates and pipes	Injured hand	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Mobilization of Geotextile material	Equipment	No equipment check was performed before use	Sudden damage	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Geotextile Exhibition	Worker	Using a cutter/knife without gloves	Hands exposed to hand equipments (cutters, scissors)	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Geotextile Splicing	Equipment	Portable sewing machine broken	Injured hand	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Splicing	Equipment	Damaged or unprotected power cord	Electric shock	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Repair Geomembrane	Material	The repair material has not cooled to the touch.	Slight burns	9	Medium
Vacuum consolidation in road	Anchor Excavation	Installation of signs	Worker	Using a hammer, drill, or manual equipment without gloves	Abrasions or hand injuries	9	Medium

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
infrastructure project							
Vacuum consolidation in road infrastructure project	Anchor Excavation	Installation of signs	Equipment	Manual equipments (hammers, drills, mallet) are damaged or loose	Loose and injure Worker	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Mobilization of vacuum pump materials & electric generators	Equipment	Generator power cable is damaged/exposed	Electric shock	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Manufacturing of electric generator stands	Worker	Not using PPE	Head, leg, skin or respiratory irritation	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Manufacturing of electric generator stands	Environment	Heavy equipment noise	Hearing disorders	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Worker	Worker working in damp area without insulating foot protection	Risk of electric shock	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Material	Generator without grounding	Cables are not labeled or phase marked	9	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Pump Running	Worker	Workers work in noisy areas without earplugs	Permanent hearing loss	9	Medium
Vacuum consolidation in road infrastructure project	Soil Investigation, Construction of Work Foundation and Joint Survey	CPT & CPTu data retrieval	Material	Oil spills contaminate soil or water	Pollution of surrounding land and water	8	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	PVD Piling	Worker	Lack of communication between equipment operators and helpers in the field	Risk of being hit, caught by equipment	8	Medium
Vacuum consolidation in road infrastructure project	Soil Investigation, Construction of Work Foundation and Joint Survey	Walk to the work area	Worker	Physical condition is not fit	Slip or stumble	6	Medium
Vacuum consolidation in road infrastructure project	Soil Investigation, Construction of Work Foundation and Joint Survey	CPT & CPTu data retrieval	Worker	Not using PPE	Injuries caused by sharp objects, falling equipments	6	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Material	Material detached from rigging gear	Crushed by load, equipment damage	6	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	rig equipment settings	Worker	Worker is under or near the load being lifted	Rig installation error	6	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	rig equipment settings	Worker	Physical fatigue or lack of focus	Wrong component installation	6	Medium
Vacuum consolidation in	Vertical Drain Installation	Check the PVD depth	Worker	Workers walking in deep mud or unstable areas	Knee or ankle injury	6	Medium

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
road infrastructure project							
Vacuum consolidation in road infrastructure project	Installation of Horizontal Drains and Pipe Networks	PHD Installation	Worker	Material exposed to the sun's heat for too long	Becomes brittle, easy to tear when installed	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Mobilization of heavy equipment & separated materials, main tank	Material	Material not properly secured on the truck	Falls during the journey	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Excavation for Separated & main tank installation	Worker	Worker slipped while going up/down into the excavation	Falling into the excavation	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Separated & main tank installation	Material	Materials are not arranged neatly around the work area	Stumble or fall	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Separated & main tank installation	Environment	The ground around the excavation is unstable	Landslide	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Inclinometer Installation	Material	Injuries caused by the sharp edges of the PVC/iron casing of the inclinometer	Injured hand	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Mobilization of Geotextile material	Worker	Workers lift or move geotextile rolls manually	Back injury	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Mobilization of Geotextile material	Worker	Fatigue due to working under the hot sun	Heat stress	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Exhibition	Worker	Fatigue due to working under the hot sun	Heat stress	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Splicing	Worker	Worker exposed to heat from welding equipment	Burns hands	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Repair Geomembrane	Worker	Worker exposed to heat from welding equipment	Mild to severe burns	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Repair Geomembrane	Worker	Non-ergonomic working position (squatting, bending for long periods)	Back injury	6	Medium
Vacuum consolidation in road infrastructure project	Anchor Excavation	Anchor Excavation	Worker	Workers are on the edge of the excavation without safety equipment.	Slipped, fell into the hole	6	Medium
Vacuum consolidation in road infrastructure project	Anchor Excavation	Anchor Excavation	Material	The excavated soil was piled too close to the edge of the hole.	Landslide	6	Medium
Vacuum	Anchor Excavation	Anchor Excavation	Environment	Vibrations from heavy	Damaging the stability of	6	Medium

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
consolidation in road infrastructure project				equipment in the vicinity	the excavation edge		
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Worker	Workers do not understand the grounding/protection system	Potential electricity leaking into the ground	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Equipment	Electrical control panel is open or damaged	Direct exposure to electric current	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Equipment	Hot equipment (generators, pumps) without sufficient ventilation	Overheating	6	Medium
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Electrical installation	Material	Loose or open cable terminals	Electric spark	6	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Mobilization of PVD materials	Worker	Working in tight areas or near heavy equipment	Worker hit by vehicle or heavy equipment	5	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Worker	Worker has no experience as a rigger	Binding error	5	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Lifting rig	Worker	Worker has no experience as a rigger	Serious accident	5	Medium
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	PVD Piling	Equipment	Operator is not certified	Risk of heavy equipment accidents	5	Medium
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Mobilization of heavy equipment & separated materials, main tank	Worker	Worker climbs onto load without safety equipment	Fall from a height	5	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Splicing	Equipment	There are no light fire extinguishers (APAR) available at the work location.	Fire is difficult to control when an incident occurs	5	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Splicing	Material	Geomembrane made from polymers (HDPE, LLDPE) melts / burns easily	Risk of fire when exposed to excessive heat	5	Medium
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Repair Geomembrane	Equipment	There is no light fire extinguisher (APAR) available	Difficult to handle small fire incidents	5	Medium
Vacuum consolidation in road infrastructure project	Soil Investigation, Construction of Work Foundation and Joint Survey	Walk to the work area	Worker	Heavy equipment or operational vehicles passing near pedestrian paths	Worker hit by vehicle or heavy equipment	4	Low
Vacuum consolidation in road infrastructure project	Soil Investigation, Construction of Work Foundation and Joint Survey	Stakeout boundary coordinates	Worker	Non-ergonomic working position (bending for long periods, standing on sloping terrain)	Back injuries, sprains, muscle fatigue	4	Low

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Mobilization of PVD materials	Material	Wet or slippery PVD	Risk of slipping when lifting	4	Low
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	PVD Piling	Worker	Workers are not focused due to fatigue	Incorrect placement of PVD	4	Low
Vacuum consolidation in road infrastructure project	Installation of Separated Tank and Main Tank	Separated & main tank installation	Worker	Fatigue due to hot weather or long working hours	Heat stress	4	Low
Vacuum consolidation in road infrastructure project	Installation of Instrumentation Equipment for Work Monitoring	Vacuum Gauge Installation	Equipment	Measuring equipment (vacuum gauge) falls or breaks	Equipment cannot be used	4	Low
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Mobilization of Geotextile material	Material	Material damaged (torn) due to being punctured by a sharp equipment	Geotextile damage	4	Low
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Geotextile Exhibition	Worker	Non-ergonomic working position (bending for long periods, standing on sloping terrain)	Back injury	4	Low
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Geotextile Exhibition	Material	Material exposed to the sun's heat for too long	Geotextile material is brittle and easily torn	4	Low
Vacuum consolidation in road infrastructure project	Installation of Protective Layer	Geotextile Splicing	Worker	Non-ergonomic working position (bending for long periods, standing on sloping terrain)	Back injury	4	Low
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Exhibition	Worker	Worker walking on geomembrane	Slipped due to slippery surface	4	Low
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Exhibition	Material	The geomembrane surface is slippery, especially when wet.	Worker slips or falls	4	Low
Vacuum consolidation in road infrastructure project	Installation of Waterproofing Layer	Geomembrane Splicing	Worker	Lack of training in the use of geomembrane welding equipment	Broken equipment	4	Low
Vacuum consolidation in road infrastructure project	Anchor Excavation	Installation of signs	Environment	Unstable/muddy soil	Risk of slipping	4	Low
Vacuum consolidation in road infrastructure project	Anchor Excavation	Embankment construction	Worker	Worker walking on unstable area	Falling into the excavation	4	Low
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Pump Running	Equipment	Vacuum pump overheating	Small fire	4	Low
Vacuum consolidation in road infrastructure	Soil Investigation, Construction of Work Foundation and Joint Survey	Stakeout boundary coordinates	Equipment	The measuring instrument (Total Station) is unstable on sloping ground.	The equipment fell and hit the worker.	3	Low

Project	*Work Package*	Activity	Hazard Type	Hazard Identification (Worker, Equipment, Material, Environment/Public)	Risk Consequences (Worker, Equipment, Material, Environment/Public)	F X D	Risk Score
project							
Vacuum consolidation in road infrastructure project	Soil Investigation, Construction of Work Foundation and Joint Survey	CPT & CPTu data retrieval	Equipment	The sounding equipment is unstable on soft ground	The appliance may tip over	3	Low
Vacuum consolidation in road infrastructure project	Vertical Drain Installation	Check the PVD depth	Equipment	Measuring equipment falls into holes or mud	Equipment damage	3	Low
Vacuum consolidation in road infrastructure project	Installation of Vacuum Pump and Electric Generator	Pump Running	Equipment	Leak in the vacuum pipe	System pressure drop	2	Low

Risk Control

Risk control in this study was implemented in accordance with the hierarchy of controls, which includes elimination, substitution, engineering controls, administrative controls, and the use of Personal Protective Equipment (PPE). The selected control measures were applied based on the specific characteristics of the hazards identified in each work activity associated with the *vacuum consolidation* ground improvement method.

By implementing appropriate risk control measures, the risk levels associated with each work activity are expected to be reduced to an acceptable level. Consequently, worker safety can be enhanced, project activities can be carried out more efficiently, and the overall success of the project can be achieved while maintaining a safe working environment.

These findings are consistent with previous studies indicating that organizational policies, safety culture, management commitment, and effective safety management systems significantly influence construction safety performance and contribute to the reduction of workplace accidents (Latief et al., 2017a; Machfudiyanto et al., 2017).

CONCLUSION

Based on the results of the study, it can be concluded that the risk assessment identified a total of 112 potential hazards associated with ground improvement works using the *vacuum consolidation* method. Among these, 4 hazards were classified as high risk, 88 hazards as medium risk, and 20 hazards as low risk. The findings indicate that activities involving heavy equipment operations, lifting activities, electrical installations, and work performed on soft ground conditions present the most significant safety risks during the implementation of *vacuum consolidation* works.

To minimize the identified hazards and risks, appropriate risk control measures were proposed and implemented. The risk control strategies adopted in this study consisted of administrative controls, engineering controls, and the use of Personal Protective Equipment (PPE). The implementation of these control measures is expected to reduce risk levels to an acceptable level, improve occupational safety performance, and support the safe and successful execution of *vacuum consolidation* projects.

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