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External Risk Factors Evaluation in Horizontal Directional Drilling Technology Using Failure Mode and Effect Analysis

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Abstract
Horizontal Directional Drilling (HDD) is a very complex technology. Although the installation of pipelines by means of this technology is often successful, examples of unsuccessful projects are also known. Due to the complexity of the technology, with the interaction of multiple processes, risks related to uncertainties in these processes play important role. These risks are related to the variability of underground strata, changing natural environment, changes in economic environment, as well as limitations of the equipment, technical disruptions and human factors. This paper describes the risk evaluation results of the FMEA and a Pareto–Lorenz analysis for 14 external risk factors (8 natural or environmental risk factors as well as 6 economic risk factors) in HDD technology. In the proposed approach not only the probability of the external risk factor occurrence was considered, but also its consequences and the ability to detect faults, which were not plainly separated and taken into account in the literature so far. Such an approach has shown the relationship between occurrence, severity and detection for the analysed external failures. Moreover, 40 detection possibilities for the external risks in HDD technology were identified. The calculated risk priority numbers enabled ranking HDD external failures and identified the most critical risks for which the suggested detection options were unsatisfactory and insufficient, and therefore other types of risk response actions need to be explored.

Keywords
Trenchless technology, Pipe laying, FMEA, Environmental risk, Economic risk, Risk evaluation.

Introduction

Horizontal Directional Drilling (HDD) is becoming more and more common trenchless technology for installing pipes under various obstacles or in the areas where open-cut methods are problematic to use. Oil, gas, water, sewage pipes, as well as casings for electrical and telecommunication cables are typically installed using HDD technology. The common HDD process consists of 3 steps: pilot bore drilling along a pre-determined and engineered alignment, reaming the hole to the required size and pulling back or insertion of the product pipe. Specialized tools and machines, such as drill rigs, steering system, tracking system, mud cleaning system, ballasting system, mud motors, and side cranes, are applied in the HDD process (Bennett & Ariaratnam, 2017). The drilling fluid is used during all the steps of the HDD process and plays a vital role in drilling, back reaming and product pipeline pullback (insertion). It flows inside of the drill string and comes out either at the drill bit nozzles, reamer nozzles or from in-string weeper subs. The drilling fluid then travels back up the borehole annulus to the surface carrying the cut rock formation spoil out of the bore. The cut material is then separated from the drilling fluid which is in turn recirculated back down the borehole. Directional steering and guidance along underground obstacles is possible in the first HDD step (pilot boring)using electronic guidance probes in conjunction with bottom hole drilling assemblies incorporating a referenced offset bias allowing directional control (Najafi, 2013). More details connected with the HDD process were given in (Willoughby, 2005). HDD equipment, tooling

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and design are constantly improving, allowing HDD crossings to be constructed over increasingly longer distances and drilling of larger diameter boreholes, as well as working in more and more demanding environment. A state-of-the-art review on modern approaches in calculating the borehole parameters, as well as the newest techniques and pipe materials that can be applied in the HDD process were presented in (Yan et al., 2018).

The external risks in HDD technology can be divided into natural, environmental and economic risks. Natural risks in the case of HDD technology are risks that exist in the ground or the surrounding area that we have no control over. The most important natural risks for HDD technology can be a result of unwanted events related to: ground water, natural topography, geology and ground formation, natural fractures, voids in the formation and the presence of gravel or cobble layers and severe weather conditions. Environmental risks the case of HDD technology are those risks that we can have some input in controlling or are areas that are at risk of being damaged from the drilling operation and that we need to put controls in place. In essence the environmental part is something we have control over or need to put controls in place to protect. The most important environmental risks for HDD technology are noise and dust in urban areas, damage existing services or ground heave due to loss of drilling fluid to the formation, negative impact to environment or a waterway due to loss of drilling fluid to the surface. Economic risks in HDD technology are related with the contract type, imprecise cost calculation for the project, insufficient available capital or cash flow for the given project, economic situation in the world (high inflation, interest rates). Imprecise cost calculation for the project may be split into several categories. 1.The experience of a particular contractor to understand a project and accurately assess the cost of construction and 2. The perception of risk for a particular project. This can vary widely depending on the experience of a contractor can in fact represent a considerable risk to both contractor and their client. Particularly in a situation where the client lacks experience and is often bound to accept the lowest price.

The aim of this work is to present a new application area of authors' risk evaluation model, namely evaluation of external risk factors in HDD technology. The assumptions for developing this model were:

- including the preventive risk management approach thanks to identifying and evaluating risk detection possibilities,
- eliminating the need to involve external experts for risk assessment,
- wide-availability of the model also for HDD projects with a modest budget,
- model simplicity enabling a preliminary risk assessment,
- versatility of the model giving the possibility of its application in different countries of the world (it is not tied to specific geographical and environmental conditions).

In this work, the Failure Model and Effect Analysis (FMEA) technique and Pareto–Lorenz analysis are applied to evaluate natural, environmental and economic risk factors in HDD technology. These methods were selected due to the simplicity of application and the fact that their application made it possible to meet the above-mentioned assumptions, as they enable risk assessment without the need to involve experts, take into account occurrence, severity and detection possibilities. The FMEA method has long been known, but it has not been applied to external risks in Horizontal Directional Drilling technology. Here, the author's concept of including this method in the risk management process is presented precisely in this technology. In this sense it is referred to as a certain novelty.

In the approach proposed in this work, risk factors prioritizing is based on 3 parameters: the probabilities of risk factors occurrence, their severity and the possibilities of detecting faults. The first two parameters were assessed based on statistical data from the conducted survey research, while the last parameter was assessed on the basis of the authors' many years of experience in HDD projects. Such an approach is dedicated for external risks evaluation of small HDD projects of low engineering complexity with modest budget (e.g. a simple 120-m HDD railway crossing), as well as for highly complex HDD projects for preliminary risk evaluation (e.g. a 1,500-m HDD crossing in highly congested urban area). The novelty in the proposed approach is the possibility to carry out risk assessment eliminating the need to engage a group of experts, as well as the fact of including in the analysis failure detection possibilities and estimating their impact on risk level. Risk detection actions play a key role in HDD projects as if they are properly introduced they are almost always cheaper and less problematic than applying risk treatment after undesirable event occurs.

Motivation to develop a new model for external risk evaluation in HDD technology

In (Willoughby, 2003) several crucial problems in HDD technology connected with natural environment were identified: for example, drilling fluid circulation loss, obstacles on the borehole trajectory, hydraulic blockage, steering problems caused by geotechnical conditions and borehole collapse. Moreover, the need to identify all potential risks, or as many as possible for HDD at the planning and design stage was indicated. It was also emphasized that it is important to take actions to reduce the identified HDD risks. In (Kruse, 2008; 2009) several important geotechnical risks were described: damage to the pipeline insulation caused by incorrect geotechnical recognition, high pulling forces or incomplete pullback due to local bore hole instability or by frictional forces in the borehole and drilling fluid runoff. In (Ariaratnam, Lueke & Anderson, 2004) authors contributed do development of risk management strategies for drilling fluid runoff by evaluating the performance of several drilling fluid mixtures in HDD projects. Bayer proposed some troubleshooting solutions for drilling fluid circulation problems, swelling of clays, as well as bore hole collapse (Bayer, 2005). In (Dong et al., 2020) a reverse circulation reaming in HDD technology was proposed, which is novel approach aiming to improve cuttings removal ability. Strater et al. identified site and subsurface characterization methods that are particularly recommended for HDD technology (Strater et al., 2006). In (Gelinas & Mathy, 2004) authors paid special attention to the appropriate design and careful interpretation of geotechnical tests results for HDD installations. Nonetheless, external risks detection possibilities in HDD technology still have not been separated from risk mitigation strategies, quantified and analyzed independently in the literature. In the case of complex and innovative construction projects careful risk assessment is especially important. If it is carried out during the projects preparation phase, it enhances desired project course (Krechowicz, 2017a; 2017b).

In the case of external risks in HDD technology it is possible that domino effect or cascading series of problems may occur. For instance, in the case of drilling in sands and gravels under the road, in addition to the drilling fluid runoff and the borehole collapsing, the soil structure may be damaged outside the drilled hole, e.g. by blurring with a ground water stream, which can lead to the creation of large voids in the ground. If the borehole and adjacent voids are not filled, e.g. with a self-hardening grout or specialist drilling mud before pulling the pipeline, then in addition to the danger caused by subsidence, the voids are a new drainage path for groundwater, which may over time enlarge and cause instability and collapse. Even a long time after the construction is completed, the road surface may be damaged or a collapse may occur, which is potentially a lethal threat to drivers. In addition, environmental risk occurrence very often leads to increasing economic risk. For instance, if a drilling fluid runoff results in a surface heave (e.g. a highway heave) then, besides of the additional costs connected with risk effect reduction, a contractor is required to cover the costs associated with highway surface reparation, compensations and changes of traffic organization, as well as with difficulties in vehicles passing. It is therefore critical to properly evaluate external risks in HDD technology prior to commencing any on site works and it could be argued that such analysis should form part of any project early design engineering.

In (Gierczak, 2014b) an expert risk assessment system for HDD technology applying Fuzzy Fault Tree analysis was shown. Its further development was presented in (Krechowicz, 2020), where risk management matrix connected with Fuzzy Fault tree were used for complex risk management in HDD process. Moreover, in (Krechowicz (Gierczak), 2021) a specific model tailored for geotechnical risk management in HDD technology was developed. It was based on a combination of hybrid Fuzzy Fault Tree and Event tree analysis. In that approaches the experts evaluate the risks individually for each examined HDD project. The risk assessment is based on their knowledge and many years of experience in HDD industry. The most important advantages of that approach are that the specificity and dynamic conditions of the particular HDD project are taken into account in the individual risk assessment. On the other hand, there is a need to engage an experienced group of experts, which can be sometimes problematic due to costs associated with their services and problems with acquiring experienced experts from the market. It was the motivation to undertake further research on the methodology of risk evaluation, in which the need to engage external experts will be reduced. Recently, an approach, which enables risk prediction in HDD projects was developed in (Krechowicz & Krechowicz, 2021), where 3 machine learning models were proposed: logistic regression model, random forests model and artificial neural network model. However, in that models, the possibilities of detecting the risks for unwanted events were not separately rated and considered.

FMEA and Pareto–Lorenz analysis applications in risk assessment

FMEA was firstly proposed by the US military in the 1940s and has become more and more popular since its adoption by the National Aeronautics Space Administration (NASA) (Mascia et al., 2020). It is it widely used as an easy method for system safety as well as reliability analysis of products and processes in various industries, especially, aerospace, automotive, nuclear, and medical (Ebeling, 2001). When applying FMEA, each component is examined to identify possible failures. In FMEA analysis three parameters are typically assessed: the probability of failure occurrence (O), the severity of the failure (S), and the possibility of detecting failure before its occurrence (D). As a result of the analysis, Risk Priority Number is generated, as the multiplication of these measures (Maddox, 2020). One of the main advantages of FMEA is the fact that it represents active attitude to coping with failures rather than reactive (Bahrami et al., 2021). It means that it takes into account the risk reduction by introducing risk responses that enable its detection, thus preventing the occurrence of this risk. The factor that distinguishes FMEA from other risk analysis techniques is that it enables identifying potential failure before its occurrence. In spite of FMEA's effectiveness in assessing risk, traditional FMEA method has also some weaknesses, such as problems with finding fault's root causes, difficulties in assessing risks accurately and defining scale criteria, the non-linear 1–10 priority scales, vulnerability to human mistake and individual judgment, equivalent importance level for all 3 metrics (occurrence, severity and detection) (Qin et al., 2020; Subriadi & Najwa, 2020).

"Pareto principle", also called 80/20 rule, was firstly applied in the analysis of quality research in 1941 by Joseph Juran, who noticed that 20% of the recognized causes leads to 80% of quality problems. It means that most causes result in slight effects and therefore it is not worth to concentrate overmuch on that group of causes. Pareto–Lorenz diagram is a popular tool, widely applied in quality management to improve quality of manufactured products and applied processes (Knights, 2001). It is important to mention that the 80/20 or 70/30 rule does not always arise, and the proportion may be different, what does not means that there was a mistake in the analysis (Roszak, 2014). When carrying out Pareto–Lorenz analysis, after identifying the problem, collecting data and identifying problem causes, they are ranked according to decreasing order of importance of their effects. Then Pareto chart for these values is created and cumulative value is calculated for each cause. Subsequently, Lorenz curve is drawn, which is a line chart for the cause effects' cumulative value (Kowalik, 2018). FMEA and Pareto–Lorenz analysis were previously used to evaluate human and equipment risk factors in HDD technology in a previous work of the authors (Krechowicz, 2021). FMEA was also applied in qualitative risk assessment of passive house design and construction processes. Its application enabled to identify causes and consequences of the most important risks in passive building production process (Krechowicz, 2020). In this work, the area of application of this model is novel, as it is applied for the first time for evaluation of external risk factors in HDD technology.

The proposed approach for external risks evaluation in HDD technology

Methodology

The research methodology consists of 7 steps:

1. External risk factors identification using surveying HDD installations.
2. Assessment of external risk factors frequency of occurrence based on the survey results.
3. Converting survey results into FMEA scales.
4. Identification of detection possibilities for external risk factors.
5. Assessment of detection possibilities.
6. Calculating risk priority number (RPN), as a product of Severity, Occurrence and Detection, to rank identified failures.
7. Carrying out Pareto–Lorenz analysis to divide external risk factors according their contribution into cumulative RPN.

The individual steps were described in detail in the following subsections.

FMEA analysis focuses on potential errors that result in failures in the implementation of planned tasks. Together with the Pareto analysis, it allows to rank these failures. The initial items from the ranking list, considered to be the most important in the Horizontal Directional Drilling process, require the indication of preventive actions. The paper presents some suggestions for such activities, referring to the causes of failures. The reasons for the failures result from the conditions for the implementation of the analyzed activity and sometimes it is difficult to clearly separate these two concepts.

External risk factors identification

14 external risk factors in HDD technology were identified based on the survey results, which was carried out among HDD contractors from 5 countries (Poland, France, the Netherlands, USA and Germany). The details of the survey were described in the author's previous work (Gierczak, 2014a). Thanks to surveying HDD contractors, the data from 5,940 HDD installations was gathered and it was possible to assess the frequency HDD failures occurrence and their severity. The list of external risk factors with division into 3 categories: natural, environmental and economic was presented in Table 1 (columns 2 and 3). The choice of 14 external risk factors factors results from the authors' experience and their practical knowledge of the HDD method – this is obviously a bit subjective, but this subjectivism is inherent in the essence of the FMEA method. Risk factors in HDD technology have been the subject of the previous surveys (Gierczak, 2014a) in which respondents had the option of adding additional risk factors, but nevertheless considered the list proposed by the author to be sufficient.

Assessment of external risk factors frequency of occurrence based on the survey results

In Table 2 values assessing occurrence and severity of failures in HDD technology were shown. The initial values of frequency of occurrence and severity (columns 4 and 6 in Table 2) are based on the survey results. The frequency of external faults occurrence expressed in % and the severity in points (1-5) were converted in the next step to 10-point FMEA scales presented in Figure 1 and Table 2.

Converting survey results into FMEA scales

Figure 1 presents the proposed FMEA scales for occurrence of environmental faults in HDD projects. The division is adapted from (Ford Motor Company, 1988). In this work, frequency of occurrence was expressed in (%) instead of in the number of cases as in the original. Table 2 shows severity and detection scales developed for HDD projects. In the case of the severity scale it is based on the criteria of the failure influence on HDD project goals (cost, schedule, quality, legal issues), as well as on the seriousness of

Table 1
List of external risk factors with division into 3 categories and their surveyed occurrence and severity

Symbol	Fault	Category	Survey results – frequency of occurrence (%)	Survey reults – severity
F25	Unexpected natural subsurface obstacles (e.g. cobblers. boulders. bedrock)	Natural	15.29	3.4
F26	Unexpected man-made subsurface obstructions	Environmental	10.59	3.1
F27	Bore hole collapse	Natural, Environmental	9.74	3.6
F28	Blocking of the drilling pipe or product pipe installation because of the swelling of clay and silt	Natural, Environmental	5.82	3.4
F29	Drilling fluid runoff	Natural, Environmental	15.28	2.7
F30	Troublesome noise	Environmental	8.44	1.4
F31	Flood	Natural	2.24	2.4
F32	Severe weather conditions	Natural	6.60	2.3
F33	Contract type (only for MAXI HDD)	Economic	11.18	1.7
F34	Incorrect cost calculations for the investment (only for MAXI HDD)	Economic	22.43	2.1
F35	Inadequate available capital (only for MAXI HDD)	Economic	18.70	2.4
F36	High interest rate (only for MAXI HDD)	Economic	5.17	1.7
F37	Variations in exchange rates (only for MAXI HDD)	Economic	5.03	1.6
F38	High inflation (only for MAXI HDD)	Economic	7.08	1.5

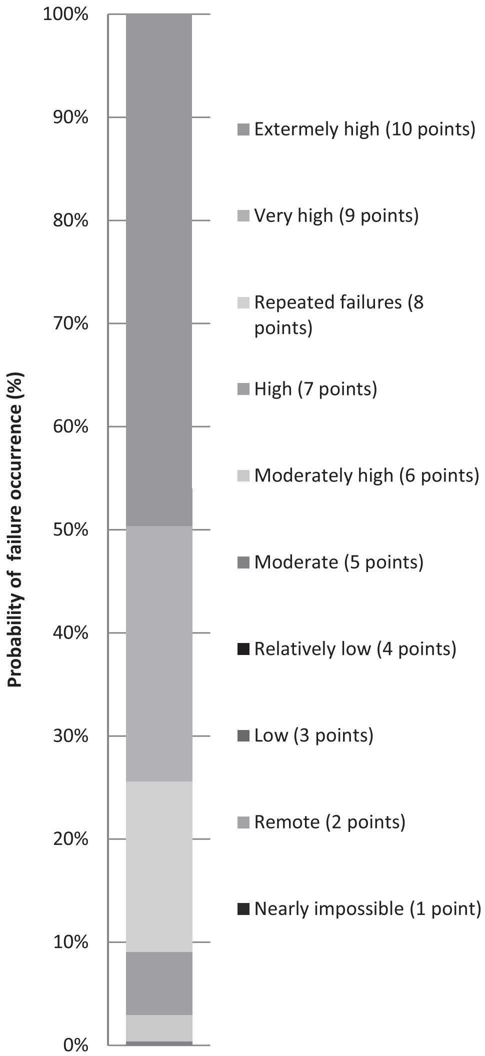

Fig. 1. FMEA scale for occurrence for HDD projects

a potential injury to an HDD crew member or a fatalities occurrence: 7–10 pts.: serious injury to HDD crew and possible fatality, 5–6 pts.: serious injury to HDD crew, 4–3 pts.: minor injury, 1–2 pts.: no injury).

In the case of the detection scale it is based on the criteria of the ability of the project team to detect a potential cause of failure or subsequent failure mode. Traditional FMEA scales (Nuchpho, et al., 2014) and specialized FMEA scales developed for construction projects (Cheng & Lu, 2015) were a basis for developing the above-mentioned severity and detection scales. The three scales were transformed and adjusted to HDD technology specificity. The survey results – the frequency occurrence and severity values were referred to the proposed FMEA scales based on the description of criteria and rank.

The surveyed probability was initially expressed as a percentage and it was needed to assign to it a point scale (1–10) according to the ranges from Figure 1. The surveyed severity was initially assessed using a 5-point scale (1 – very low, 2 – low, 3 – medium, 4 – high, 5 – very high). It was converted into scores (1–10) according to the traditional FMEA scale by doubling the original score obtained from the analysis of the survey results and rounding the result to the whole unit. The values assessing occurrence and severity in HDD technology expressed in FMEA scales were presented in Table 3.

Table 2
FMEA scale for severity and detection in HDD projects

Severity scale	Severity rank	Detection scale	Detection rank
Hazardous	10	Absolute uncertainty	10
Serious	9	Very remote	9
Extreme	8	Remote	8
Major	7	Very low	7
Significant	6	Low	6
Moderate	5	Moderate	5
Low	4	Moderately high	4
Minor	3	High	3
Very mintor	2	Very high	2
None	1	Almost certain	1

Table 3
The values assessing occurrence and severity in HDD technology expressed in FMEA scales

Symbol of the fault	Occurrence in FMEA scale (O)	Severity in FMEA scale (S)
F25	8	7
F26	7	6
F27	7	7
F28	7	7
F29	8	5
F30	7	3
F31	6	5
F32	7	5
F33	7	3
F34	8	4
F35	8	5
F36	7	3
F37	7	3
F38	7	3

Identification of detection possibilities of external risk factors in HDD technology, their limitations and assessment

Detection in this work is defined as actions which aim is to find out or discover early a certain failure. Such actions belong to risk cause reduction according to risk treatment nomenclature. In detection actions should not be included any actions targeting at stopping the failure which has already occurred, as such actions are classified as risk effect reduction, risk transfer and risk elimination. Table 4 presents the list of actions that were aimed to detect failures as well as values that were proposed to assess the difficulties of detection (D). Own authors' experience in HDD industry, the conversation with the HDD specialists allowed to determine the appropriate values of the D parameters.

Geology possibly represents the single largest risk to HDD projects as it determines almost every aspect of the approach to designing a constructible bore to actually managing the risks both perceived and real on the project site. In terms of risk detection and evaluation there is firstly investigation through geophysical investigation and borehole coring to establish the type and extent of the geological conditions. We can use the boreholes to investigate the extent of ground water and gravels. These natural risks can not be avoided. We can only understand their type and extent. Once we have information on the natural risks that might exist on a project we can then consider how best to manage and mitigate these local environmental risks with regards to completing the project with respect to the natural risks. That is why in the case of HDD technology proper detection is vital.

One of detection limitations is the fact that sampling cannot be carried out exactly at the borehole trajectory, as wells would be an escape route for the drilling fluid. Samples should be taken from wells located at certain prescribed distances from the borehole trajectory (7.62–55.72 m) (Strater et al., 2006). The fact of testing not directly on the HDD alignment contributes to the increase of the uncertainty of geotechnical tests. Moreover, there are problems with testing under obstacles and limit of test depth of the geotechnical tests.

The practice shows that the test depth limit are e.g. 10 m with a probe generating an electromagnetic field, the limitation for GPR are low resistance soils (clay), for electrofusion imaging clay soils are not limited, the depth of GPR testing to several dozen m,accuracy decreases with increasing depth, profiling and electromagnetic mapping to a depth of 10 m.Apart from this, the results of geotechnical survey may be misinterpreted by inexperienced HDD operators. Besides this, detection effectiveness of drilling fluid runoff thanks to calculating maximum and minimum allowable downhole pressure may be subjective, as they are dependent on the fracture model being used, as not all models fit all circumstances. All of these factors contribute to the decrease of detection effectiveness. During test boring or geotechnical investigation drilling is it also important to investigate the ground conditions to a depth greater than the initial design depth. This then allows design flexibility if the investigation shows problematic conditions. If the depth of trial investigation is not at least to the depth of the planned bore the rate of detection of the risk will decrease significantly, greatly increasing the risk to the project outcome. In the case of the possibilities of detection of incorrect cost calculations for the investment, they depend on the ability of a contractor to track costs and also to compare against budgets. It sounds simple but not all contractors are also capable accountants.

In the case of swelling clays, tests on sample cores called pin hole dispersion tests can provide a piece of suitable information needed to assess the ground swelling potential. While the testing is possible and the results are very informative, the question is to what extent expensive investigation bores are done in practice and to what extent special tests are carried out. In the most cases special tests are not performed, so the detection of swelling clay is low, and then the consequence of not putting mitigation controls in place is very high, e.g. stuck pipe and fracouts. All in all, limitations in the project's budget can significantly lower the effectiveness of the detection actions in HDD technology. The detection values proposed in column 3 in Table 4 reflect the effect after applying the most suitable detection actions, which were listed in column 2 in Table 4. It must be stressed that if the contractor, owner or designer is not going to apply those actions in a certain HDD project due to limited budget or for other reasons, the detection possibilities may be significantly lower, which translates into higher values on the FMEA scale for detection. Individual values for detection possibilities may be adjusted to the analyzed projects, taking into account the their budget and specific conditions of investment realization.

The list of 40 possibilities of risk detection results from the authors' experience, observation and analysis of many cases of HDD technology installations. In some cases, when the score for the possibility of detecting the risk is high in Table 4, the presented reactions are not sufficient and it is recommended to look for methods of risk response other than detection (reduction of the effect, risk transfer or risk elimination).

Table 4
Possible actions aiming to detect failures in HDD technology and the proposed values assessing difficulties of detection of failure modes (D)

Failure symbol	Possible actions aiming to detect failure	Detection in FMEA scale (D)
F25	• Carrying out literature studies, gathering historical data, interviewing residents • Checking the references and certificates of the company conducting geotechnical investigations • Carrying out appropriate geotechnical tests (field tests, laboratory testing – soil grain size distribution, soil plasticity, soil density, distribution of subsurface deposits, geophysical testing – Electrical Resistivity Tomography, Seismic Refraction, Downhole Velocity Surveys, Electromagnetic survey, Ground Peneratration Radar • Checking if an experienced geotechnician is employed to get a proper interpretation of the results of geotechnical survey • Carrying out a trial drilling	4
F26	• Carrying out literature studies, gathering historical data, interviewing residents • Checking the references and certificates of the company conducting geotechnical investigations • Using several methods of locating underground urban infrastructure (e.g. Ground Penetration Radar (GPR), electrofusion profiling and electrofusion probing, thermal imaging cameras, methods with an induced electromagnetic field) • Employing an experienced geotechnician to get a proper interpretation of the results of geotechnical survey • Carrying out a trial drilling • Exposing and monitoring the existing underground infrastructure located close to the HDD alignment • Checking if augmented reality is applied to increase the drill rig operator's awareness of the identified underground utilities	3
F27	• Carrying out proper geotechnical tests to detect if there is lack of natural cohesion of the grains, if there is homogenous grain-size distribution, if there are oversize materials, particle size distribution • Checking if an experienced geotechnician is employed to get a proper interpretation of the results of geotechnical survey • Using a pressure monitoring system to get precise information about the bottom pressure under static conditions and during circulation in the borehole	5
F28	• Assessment of the ground swelling potential based on the results of tests on sample cores called pin hole dispersion tests • Using a pressure module to get precise information about the bottom pressure under static conditions and during circulation in the borehole	3
F29	• Calculating the maximum allowable pressure and the minimum required downhole pressure and using a pressure monitoring system	6
F30	• Checking and assessing the situation of the building site in connection with special requirements of noise emission (e.g. close to the environmentally sensitive areas or housing estate) • Checking if the period of the drilling works falls on the birds breeding season • Checking noise emission specification of the HDD equipment and the possibilities to use the noise reduction system	4
F31	• Checking the weather forecasts and alerts of the Institute of Meteorology and Water Management or other appropriate institutions such as water boards	3

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Table 4.
Possible actions aiming to detect failures in HDD technology and the proposed values assessing difficulties of detection of failure modes (D)

Failure symbol	Possible actions aiming to detect failure	Detection in FMEA scale (D)
F32	• Checking the weather forecasts and alerts of the Institute of Meteorology and Water Management or another appropriate institution • Assessment of hazards connected with particular seasons (low temperatures influence on: plastic pipe storage, fusion process, maintenance of the equipment; strong wind influence, heavy rainfall or snowfall influence on pipe connections) and possibilities of introducing measures to protect against them	3
F33	• Checking the type of contract and its specificity (turkney contracts, footage contract, daywork contracts) • Checking the accuracy of technical specifications, drawings and the scope of work • Checking and assessing the entries in the contract (risk sharing, risk transfer, contractual penalties for failure to meet deadlines, additional compensation due to differing ground conditions, type of contract)	2
F34	• In the case of HDD projects that require very high financial expenses connected with using large amounts of materials it is recommended to accurately definite the break-even point of the investment, carry out the cost planning carefully • Checking if all required information was given to the contractor by an owner before the tender (e.g. limited geotechnical information or borehole information that is considerably offset from the bore alignment or core information that does not go as deep at the planned HDD bore are inadequate) • Checking if risk sharing between an owner and contractor is going to applied in the project • Engaging a competent HDD specialist who can assist in finding the balance of factors that suit the available information and the risk appetite for both parties	5
F35	• Checking the contractor's and designer's financial standing • Checking the owner financial standing, • Checking in what way the contractor was paid in a last contract: getting paid a percentage of the works completed each month can smooth out the cash flow on the job rather than getting a big payment at the completion of the pilot hole, the completion of the reaming and the completion of the pipe pullback. • Checking the way of planned risk transferring in the contract and in the previous one– if the owner planned to have payment schedules heavily weighted to installation of a pipeline, they should be responsible enough to only engage a contractor that has a sufficiently large capital funds account to cash flow the project. Engaging small, cheap contractor in such a case is likely to cause problems	3
F36	• Checking if the HDD equipment was purchased on credit and monitoring interest rates as well as their forecasts	3
F37	• Checking if the HDD equipment was purchased on credit in foreign currency and monitoring exchange rates as well as their forecasts • Checking if contracting is carried out in commonly traded currencies USD, EUR, CAD, GBP, AUD	3
F38	• Inflation monitoring in the case of long, costly HDD projects • Checking the region, in which HDD installation is carried out (nowadays inflation is an issue in some African countries), • Checking if internationally traded currencies USD, EUR, CAD, GBP, AUD like are going to be used	3

FMEA evaluation results for external risks in HDD technology

In Table 5 the evaluation results for HDD technology (Occurrence, Severity, Detection, Risk Priority Number and Priority) were shown. Risk Priority Number (RPN) was calculated as a product of Severity, Occurrence and Detection.

Table 5
The evaluation results for external risks in HDD technology (Occurrence, Severity, Detection, Risk Priority Number and Priority)

Failure symbol	O	S	D	RPN	Priority
F25	8	7	4	224	3
F26	7	6	3	126	6
F27	7	7	5	245	1
F28	7	7	3	147	5
F29	8	5	6	240	2
F30	7	3	4	84	10
F31	6	5	3	90	9
F32	7	5	3	105	8
F33	7	3	2	42	12
F34	8	4	5	160	4
F35	8	5	3	120	7
F36	7	3	3	63	11
F37	7	3	3	63	11
F38	7	3	3	63	11

where: O – Occurrence; S – Severity; D – Detection.

Pareto–Lorenz analysis

Pareto–Lorenz analysis was conducted to enable external risk factors division based on their contribution into cumulative Risk Priority Number. Pareto–Lorenz chart for external risk factors in HDD technology was presented in Fig. 2. External failures in HDD technology, which elimination is vital for risk reduction, were placed in Class A, failures of secondary elimination significance were placed in Class B, and failures elimination of which leads to the lowest risk reduction in the analyzed technology were placed in Class C. When assigning failures to individual classes in terms of quantity and value criterion, a certain discrepancy was found out. Pareto analysis, which was carried out in terms of the number of external risks causes (types of failures) revealed that:

- 21% of causes (failures) generate 40% of effects (RPN+),
- next 29% of causes (failures) generate 31% of effects (RPN+),
- the remaining 50% causes (failures) generate 29% effects (RPN+).

Pareto analysis, which was carried out in terms of in terms of the value of failure effects (RPN+) revealed that:

- 50% of causes lead to 71% of effects (RPN+),
- next 29% causes lead to 20% effects (RPN+),
- the remaining 21% causes lead to 9% effects (RPN+).

Supposing that group A should include causes contributing up to 30% of failure types, this group should enclose such failures as F27 (Bore hole collapse), F29 (Drilling fluid runoff), F25 (Unexpected natural subsurface obstacles. Supposing that group B should include causes contributing up to 20% of failure types,

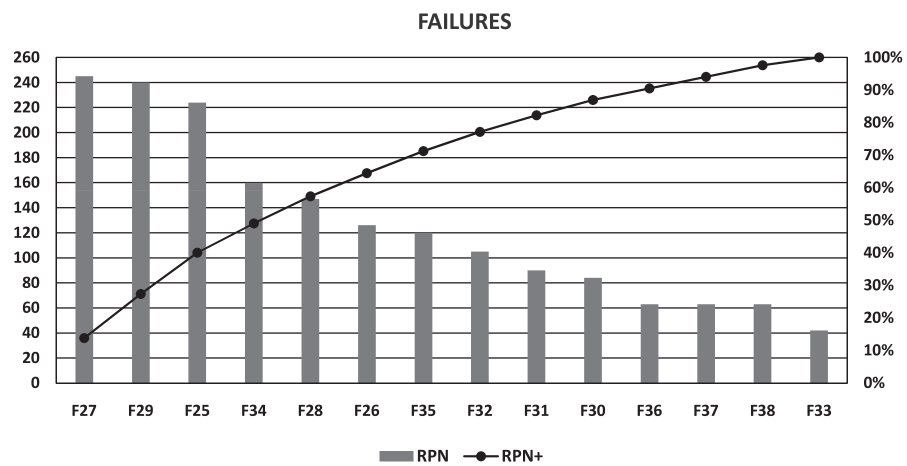

Fig. 2. Pareto–Lorenz chart of RPN for external failures in HDD technology

this group should enclose such failures as: F34 (Incorrect cost calculations for the investment), F28 (Blocking of the drilling pipe or product pipe installation because of the swelling of clay and silt), F26 (Unexpected man-made subsurface obstructions), F35 (Inadequate available capital). Assuming that group A should enclose failures generating up to 70% of all effects (RPN+), it should contain all failures which were assigned to group A and B in terms of the number of external risks causes. In the analyzed case, the criterion of the number of types of failure is more informative, as it allows to identify a limited number of the most significant types of failures.

Summary

The introduced risk evaluation model for external risks in HDD technology targets to give a helping hand to specialists in HDD technology and managers who are willing to create achievable and successful projects. This model dealt with the evaluation of a specific group of risks in HDD technology, namely external risks, in which it is possible that domino effect or cascading series of problems may occur, leading to serious technical disruptions, adverse impact on the natural environment and surroundings, as well as severe economic consequences. In this work 40 detection possibilities of external risk factors in HDD technology were identified and assessed. Moreover, limitations in detection possibilities effectiveness were indicated. It should be stressed that if not all recommended methods of detecting individual risks (listed in Table 4) are planned to be applied in the analyzed project, the possibility of detecting the risk should be adjusted to the project needs, therefore it should be lowered, which translates into higher values on the FMEA scale for detection. In this way dynamic risk assessment could be enabled. The application of the proposed risk evaluation model based on FMEA with Pareto–Lorenz analysis allowed to consider not only occurrence and severity of the risk factors but also their detection possibilities and finally led to identifying the most critical external risk factors in HDD technology: F27, F29, and F25. In the case of this group of critical external risks it is advised to work on new effective detection techniques or search for risk treatment possibilities beyond risk cause reduction, such as the reduction of risk effect, risk elimination, risk transfer, or active acceptance of risk. The presented approach can be useful for making evaluation or preliminary risk evaluation of external risks in MINI, MIDI and MAXI HDD projects, in which expert risk assessment is not possible, mainly due to the limited budget and problems with recruiting qualified experts from the industry. All in all, this work together with its previously published part concerning human and equipment risk factors (Krechowicz et al., 2021) is a comprehensive response to industry demand for a risk assessment model for human, equipment and external risks evaluation model, in which the need to involve external experts will be avoided. The presented risk management model for Horizontal Directional Drilling processes has a certain utility value. The lack of descriptions of other external risk management models not requiring the involvement of experts for risk assessment in this technology in the literature justifies the statement that it is, however, a significant utility value and constitutes a certain new approach to this issue.

Moreover, in this work it was noticed that in the analyzed failures there were pairs, which had similar RPN value (e.g. RPN(F27)=245 and RPN(F29)=240, RPN(F26)=126 and RPN(F35)=120; RPN(F31)=90 and RPN(F31)=84), but different interpretations and miscellaneous semantic risk implications. F27 was associated with higher risk than F29, despite the fact that its occurrence was lower than for F27. It was due to differences in their values of severity and detection. Similar observation was made for F26 and F35, as well as F31 and F30. In some cases, the above mentioned discrepancies in RPN interpretations could even result in omitting or underestimation of a high-risk event, which when occurred could cause high costs.

There is a risk inherent in the FMEA technique and the Pareto–Lorenz analysis that certain risk factors for which the RPN has a low value will be neglected. Therefore, it is necessary, based on experience, to consider whether such a situation does not occur in a specific case. FMEA and Pareto–Lorenz analysis should be considered as decision support tool, not the final firm verdict.

The main drawback of the application of FMEA method in the case of risk assessment is connected with basing on statistical approach (survey results) when calculating the values of occurrence and severity. However, such approach in most cases allows to properly reflect the statistical view of faults, it might not be satisfactory and well suited for the specificity of every HDD project. It can lead to deviations of RPN results for some HDD projects, which differ statistically from typical ones (the main differences may include challenging diameter or installation length, varying ground conditions). Perhaps the assessment of the term "severity" is subjective. However, in the FMEA method, many elements of the assessment are subjective and depend on the experience of the analysis team.

Future works are planned regarding to the demonstration of the effectiveness and efficiency of the proposed method by comparing the analysis results with the real HDD project run. Regarding to the effectiveness of implementing the risk responses proposed by the authors, it was proved and demonstrated on the example of several HDD installations in Australia, Mexico, Poland and Thailand in the author's previous works (Krechowicz 2017a; 2017b). Authors' practical experience in HDD installations and individual risk assessments carried out by the authors based on the analysis of the project documentation and the failure tree analysis presented in author's previous work (Krechowicz, 2020; Krechowicz (Gierczak), 2021) show that the risk factors which obtained the highest RPN in this work (such as bore hole collapse, drilling fluid runoff, unexpected natural subsurface obstacles, incorrect cost calculations for the investment) were associated with high probability of occurrence in many analyzed HDD projects. Practice shows that their effects are severe for contractors, and careful selection detection possibilities is needed. It was observed by the authors on many HDD projects. When detection possibilities were properly applied, the unwanted events did not occur. In the case when the proposed detection possibilities were not applied, unwanted events occurred.

Future research is oriented in developing a comprehensive holistic risk management system based on machine learning models. In addition to eliminating experts, such a system will allow for dynamic risk assessment based on comparison of the risk response options for unwanted events. Thanks to the diversified selection of HDD installations in the training set, this system may enable to obtain very good results also for specific HDD installations.

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