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

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Abstract
Horizontal Directional Drilling (HDD) technology is a highly complex process connected with high risk and uncertainty due the high variability underground strata, often limited access to specialised equipment, dynamic natural environment, technical disruptions, human factor and changes in economic environment that further complicate the gathering of reliable information and data. This work presents a new risk evaluation model tailored for HDD technology, in which failure mode and effect analysis (FMEA) modelling were applied. This paper focuses on 15 human risk factors and 9 equipment risk factors in HDD technology. The proposed approach takes into account not only the probability of the risk factor occurrence, but also its severity and the possibility of detecting faults, which were not clearly separated and analyzed in the previous works. Application of the proposed model shows the relationship between occurrence, severity and detection for the analyzed failures. Moreover, many detection possibilities for the identified failures were presented. The calculated risk priority numbers allowed to rank HDD failures and identify the most critical risks for which one should look for risk treatment possibilities beyond risk cause reduction, such as risk effect reduction, risk transfer, risk elimination or active risk retention.

Keywords
trenchless technology, pipe laying, FMEA, risk management, risk evaluation.

Introduction

Horizontal Directional Drilling (HDD) is nowadays one of the most popular trenchless technologies for installing pipes and conduits under various obstacles or in the areas where open-cut methods are difficult to apply. Pipes transporting oil, gas, water, sewage, casings for electrical and telecommunication cables are commonly installed using this technology. The typical HDD process includes 3 steps: pilot bore drilling along a desired directional path, reaming the hole to the desired diameter and pulling back the product pipe. The whole process is accomplished using specialized tools and machines, such as drill rigs, steering systems, tracking systems, mud motors, mud cleaning systems, ballasting systems, side cranes. During all the steps of the HDD process the drilling fluid is pumped down the inside of the drill string and comes out either at the drill bit or reamer. The HDD trajectory may be straight or curved or a 3D combination, and the direction of the drilling head can be adjusted during the pilot hole drilling phase, which enables steering around natural or man-made obstacles. Najafi (2013) presented more detailed description of HDD process. Bennett and Ariaratnam (2008) focused on HDD equipment and materials, as well as on bore planning issues. Willoughby (2005) presented the history, applications, as well as important issues connected with the technical feasibility of HDD projects. HDD equipment and contractor capabilities are constantly improving, enabling drilling projects with increasingly larger diameters and lengths. As the tech-

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nology has developed the drilling requirements have become much more demanding.

In many instances HDD contractors compete in a lowest cost tender evaluation to gain the work. In many instances this is the start of a compounding risk structure. Asset owners and stakeholders must not assume that all contractors have equal capability and certainly should understand that each contractor will view risk differently based largely on past experience, or lack of it. Many newer contractors with less knowledge and experience will not assess the potential risks of a particular project simply based on the fact they just do not know the potential of what could possibly go wrong. In this case they perceive low risk and may price a project accordingly. These are the contracts that often develop problems and end up in legal determinations.

Who is to blame in this case?

The contractor for not assessing the risk? – quite possibly they didn't know in the first place.

The client / asset owner for not doing due diligence on the contractors real experience and if the client does not have that capability and outsources the evaluation to an HDD specialist.

It is also important to check if the chosen HDD specialists have the required knowledge. There are many examples of HDD specialists that claim to have experience in a particular type of project and then poorly advise their client who in turn may incorrectly advise their client who in turn incorrectly appoints an HDD contractor – generally based on the lowest price. A cascading and compounding series of risk perception based on the perceived knowledge of and industry expert. For an example, just because a person may be able to drive a car does not mean they are a racing expert that can advise a whole racing team on the many complexities of winning a specialized race. Recently there have been many examples of HDD experts that have mini rig experiences advising clients for complex maxi rig projects with less than stellar outcomes.

The aim of this work is to present a new risk evaluation model tailored for human and risk factors in HDD technology, in which Failure Mode and Effect Analysis (FMEA) modelling were applied. The proposed approach makes it possible to make a preliminary evaluation of the risk in the project and is focused in particular on HDD projects with a modest budget, in which a group of experts could not be involved in risk assessment process, for many reasons but principally limited budget In addition, the proposed approach allows for taking into account the severity of the risk factor and the possibility of detecting faults, which were not plainly separated and analyzed in the previous works. Such an approach allows to rank HDD failures and identify the most critical risks for which one should look for new detection techniques or other risk treatment possibilities.

Literature review

Risk evaluation in HDD technology

In (Willoughby, 2005) some problems that can lead to the failure in HDD technology were identified: 1) loss of drilling fluid circulation in the borehole, 2) obstacles on the borehole trajectory, 3) hydraulic blockage, 4) steering problems, 5) borehole collapse, 6) pipeline damage. It was stressed that there is need to identify all potential risks for HDD at the planning and design stage. The need to take actions to reduce the risk was also emphasized. In (Kruse 2008, 2009) several important risks in the pull back phase in the HDD installation were identified: 1) inadequate ballasting of the pipeline, 2) acceptance or designing of too small bending radius, 3) damage to the pipeline insulation due to incorrect geotechnical recognition, 4) high pulling forces or incomplete pullback caused by local bore hole instability or by frictional forces in the borehole and drilling fluid seepage. Some risk mitigation possibilities for the identified risks were also presented. Several troubleshooting solutions for loss of circulation, hydrolock, bore hole collapse, drill tool and product pipe failure, as well as heaving were shown in (Najafi, 2013). Ariaratnam, Lueke add Anderson (2004) assessed the performance of different combinations of drilling fluids in HDD installations in gravel conditions, which is valuable for development proper risk mitigation strategies. Some important solutions helping to cope with loss of circulation, ground swelling, and bore hole collapse were proposed in (Bayer, 2005). Moreover, some recommendations concerning site and subsurface characterization methods suitable for HDD process were given by Strater, Dorwart and Brownstein (2006). Some valuable information concerning proper design and interpreting geotechnical investigations for HDD projects were presented in (Gelinas and Mathy, 2004). Current trends in pullback loads, borehole stability and borehole mud pressure estimation models, as well as innovative solutions (such as reverse circulation system, Direct Pipe applications, push hole opening and new materials) that can improve the HDD process performance and therefore reduce risk were discussed by Yan, Ariaratnam, Dong and Zeng (2018). In (Dong et al., 2020) a performance analysis of a solution for improving cuttings removal ability in HDD process, namely reverse circulation reaming, was shown.

A novel reverse-circulation reamer was built, which improves the cutting transport efficiency and therefore can contribute to risk reduction. Wiśniowski, Łopata and Orłowicz (2020) proposed a new numerical method for optimization of the HDD alignment, which benefitted from a chain curve trajectory and its implementation was considered as easier, thus can be burdened with lower risk. In (Krechowicz, 2017a, 2017b) it was proved that proper risk assessment carried out in projects preparation stage in the case of complex and innovative construction projects supports desired project course. Nevertheless, fault detection possibilities in HDD technology have not been separated from risk mitigation strategies, quantified and analyzed individually in the literature so far.

In (Gierczak, 2014b) a risk assessment model in HDD technology using Fuzzy Fault Tree analysis was presented. In (Krechowicz, 2020) a comprehensive risk management model dedicated for HDD technology was proposed, in which Fuzzy Fault tree analysis, risk management matrix and fuzzy weighted risk index were applied. In (Krechowicz, 2021) a risk management model dedicated for geotechnical risks in HDD technology was shown, in which hybrid Fuzzy Fault Tree and Event tree anlalysis were applied for geotechnical risk assessment in HDD projects. In all presented models, the risk evaluation is based on the opinion of experts who assess the risk individually for each analyzed HDD project. This approach allows accurate risk levels allocation for individual events, taking into account the specific and dynamic conditions in which the analyzed installation is carried out within the boundaries of a particular HDD project. On the other hand, this approach requires the involvement of an experienced group of experts, which is sometimes difficult considering costs associated with engaging industry specialists. In the previous works the severity of the risk factors and the possibility of detecting faults were not plainly allocated and or analyzed. Taking into account severity and detection possibilities may be very valuable in prioritizing risk factors. As such, there is a need to develop new risk evaluation models that could be applied in HDD projects with modest budget for preliminary risk evaluation in HDD technology. For such projects it is especially important to consider detection possibilities of failures, as properly applied detection actions are almost always significantly cheaper and less troublesome than treating risk after an unwanted event occurrence. It can be especially useful and sufficient for small HDD projects of low value and low engineering complexity, for example, a simple 150m straight shallow road crossing. In the case of large and HDD installations and HDD installations of high complexity (for example 2000 m river crossing in rocks in sensitive environment), it can be used only for preliminary risk assessment.

FMEA technique and Pareto–Lorenz analysis

FMEA technique is usually applied to define, identify and eliminate known or potential failures and is intended to enhance the reliability and safety of the systems (Chin, Chan and Yang, 2008). It aims to provide information for making decisions in the risk management process (Nuchpho, Nansaarng and Pongpullponsak, 2014). Unlike other risk assessment instruments which search for solutions after a certain failure occurred, FMEA allows to identify potential failure before it happens and assess risk associated with its occurrence (Qin, Xi and Pedrycz, 2020). Due to the fact that FMEA results can be a source of valuable information for designers, contractors, and engineers helping them to improve their projects. This technique is widely used in engineering systems as well as in aerospace, chemical, mechanical and medical industry (Liu and Deng and Jiang, 2017). The system reduces potential loss and supports decision makers indentifying the proper preventive measures to improve the emergency response capability. In traditional FMEA each failure mode is defined by three parameters: likelihood of occurrence (O), severity (S), and difficulty of detection (D). Those 3 parameters are used to describe each failure mode. Each of these factors is usually evaluated using the 10-point scale. In traditional FMEA Risk Priority Number (RPN) is widely used to evaluate risk priority. It is a mathematical product of O, S and D and is usually expressed as: $\mathrm{RPN} = \mathrm{O} \times \mathrm{S} \times \mathrm{D}$. RPN allows to obtain a ranking order among identified failures. If the calculated value of RPN for a certain failure is higher than others, it is determined to have higher risk and should be given more attention and more often that not will require intervention or risk reduction action. Although FMEA is effective in measuring risk, it has also some shortcomings. In (Subriadi and Najwa, 2020) some weaknesses of traditional FMEA methods were presented, such as difficulties in finding fault's root causes, problems with assessing risk factors accurately and giving scale criteria, the non-linear 1–10 priority scales, susceptibility to human error and individual opinion, equal importance level for all 3 parameters (occurrence, severity and detection).

Pareto principle was stated by a nineteenth-century Italian economist Vilfredo Pareto, who, analyzing the distribution of income of the population, noticed that 80% of wealth is possessed by 20% of the population (Borkowski, 2013). In 1941, Joseph Juran used the term "Pareto principle" in the analysis of quality research for the first time, noting that 80% of quality problems are caused by 20% of the identified causes (Bociąga and Klimecka-Tatar, 2016). The interpretation of the 80/20 rule is that most causes generate minor effects and it is not efficient to focus too much on that group of causes. Pareto–Lorenz diagram is one of the most commonly used traditional tools applied in quality management to increase the level of product quality and process improvement (Knights, 2001). Pareto–Lorenz analysis consists of the following steps:

1. Problem identification;
2. Data collection;
3. Causes identification;
4. Ordering the causes in decreasing order of importance of their effects;
5. Creating a bar chart for these values (Pareto chart);
6. Calculating the cumulative value for each cause;
7. Creating a line chart for the cumulative value of each cause effect (Lorenz curve),
8. Analysis of the diagram (Kowalik, 2018).

When carrying out Pareto analysis, it should be noted that the 80/20 or 70/30 ratio does not always occur (it may be a different proportion) and it does not constitute an error in creating the analysis (Roszak, 2014).

The proposed model for human and equipment risk evaluation in HDD technology

The research methodology

In the author's previous work (Gierczak, 2014a) 38 various failures in HDD technology were identified. They can be divided into 4 categories: 1) human, 2) equipment, 3) natural environment and 4) economic environment risk factors. Due to the number of potential risk factors, this work will focus on human and equipment risk factors. Risk factors connected with natural and economic environment will be the subject of another work. In some cases a single risk factor could be categorized to more than one category. In such a case, the predominant and most important category was chosen, e.g. in the case of downtime in the HDD process, human factor is predominant and the most important, as it is the human factor that controls almost all aspects for the project.

The research methodology is presented in Fig. 1.

Thanks to surveying 5,940 HDD installations from 5 countries (Poland, France, the Netherlands, USA, Germany) it was possible to assess the frequency of the occurrence of failures in HDD technology and the influence of failure occurrence on the whole HDD project failure. Tables 1–3 present the proposed FMEA scales for occurrence, severity and detection in HDD projects. They are based on traditional FMEA scales: scale of occurrence from Ford Motor Company (1988) and benefit from specialized FMEA scales dedicated to construction projects (Cheng and Lu, 2015). They were modified in order to adjust to HDD technology specificity. In this work, the scale of occurrence was expressed in (%) instead of in the number of cases as in the original (Ford Motor Company, 1988). The description of criteria and rank were created so that the results of the survey conducted by one of the authors of this work (frequency of failure occurrence and severity) (Gierczak, 2014a) could be referred to these scales.

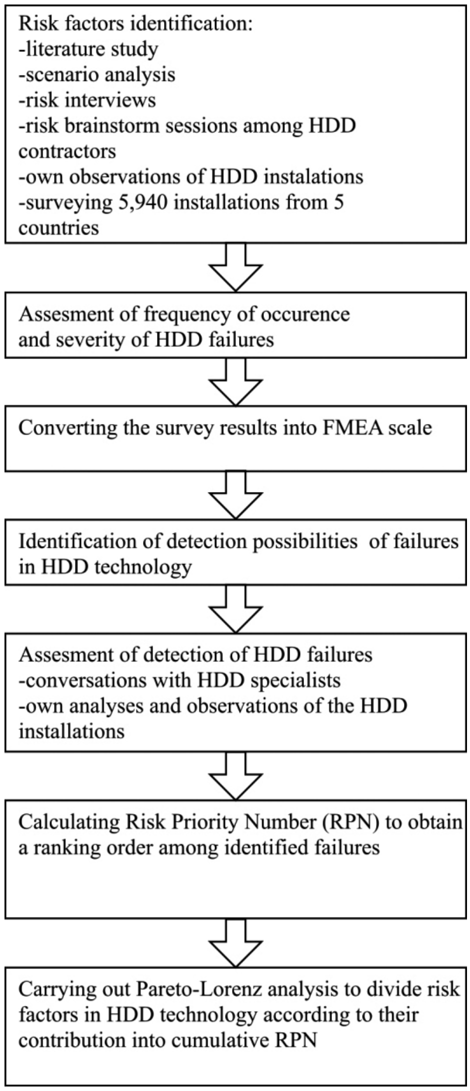

Fig. 1. The research methodology

Table 1
FMEA scale for occurrence for HDD projects (adapted from Ford Motor Company (1988))

Occurrence scale	Criteria: probability of failure (%)	Rank
Extremely high: Failure almost inevitable	⟨50; 100⟩	10
Very high	⟨33.30; 50.00)	9
Repeated failures	⟨12.50; 33.30)	8
High	⟨5.00; 12.50)	7
Moderately high	⟨1.25; 5.00)	6
Moderate	⟨0.25; 1.25)	5
Relatively low	⟨0.05; 0.25)	4
Low	⟨0.0067; 0.05)	3
Remote	⟨0.00067; 0.0067)	2
Nearly impossible	⟨0; 0.00067)	1

Table 2
FMEA scale for severity for HDD projects

Severity scale	Criteria: severity of effect	Rank
Hazardous	Disastrous influence on HDD project goals (cost, schedule, quality; legal issues); serious injury to HDD crew and possible fatalities	10
Serious	Serious effect on HDD project goals (cost, schedule, quality legal issues); serious injury to HDD crew and possible fatalities	9
Extreme	Severe effect on HDD project goals (cost, schedule, quality, legal issues); serious injury to HDD crew and possible fatality	8
Major	Major influence on HDD project goals (cost, schedule, quality, legal issues); serious injury to HDD crew and possible fatality	7
Significant	Significant effect on HDD project goals (cost, schedule, quality, legal issues); serious injury to HDD crew	6
Moderate	Moderate effect on HDD project goals (cost, schedule, quality, legal issues); serious injury to HDD crew	5
Low	Small effect on HDD project goals (cost, schedule, quality, legal issues); minor injury to HDD crew	4
Minor	Minor effect on HDD project goals (cost, schedule, quality, legal issues); minor injury to HDD crew	3
Very minor	Very minor effect on HDD project goals (cost, schedule, quality, legal issues); no injury to HDD crew	2
None	No effect	1

Table 3
FMEA scale for detection for HDD projects

Detection scale	Criteria	Rank
Absolute uncertainty	The project team is unable to detect a potential cause of failure or subsequent failure mode	10
Very remote	The project team has very remote chance to detect a potential cause of failure or subsequent failure mode	9
Remote	The project team has remote chance to detect a potential cause of failure or subsequent failure mode	8
Very low	The project team has very low chance to detect a potential cause of failure or subsequent failure mode	7
Low	The project team has low chance to detect a potential cause of failure or subsequent failure mode	6
Moderate	The project team has moderate chance to detect a potential cause of failure or subsequent failure mode	5
Moderately high	The project team has moderately high chance to detect a potential cause of failure or subsequent failure mode	4
High	The project team has high chance to detect a potential cause of failure or subsequent failure mode	3
Very high	The project team has very high chance to detect a potential cause of failure or subsequent failure mode	2
Almost certain	The project team control will almost certainly detect a potential cause of failure or subsequent failure mode	1

Assessment of occurrence and severity of human and equipment risk factors in HDD technology

Table 4 presents the values assessing occurrence and severity of failures in HDD technology. The survey results – frequency of occurrence expressed in % and severity expressed in points (1–5) were converted to FMEA scales presented in Tables 1–2. The probability expressed as a percentage was assigned a point scale (1–10) according to the ranges from Table 1 in which it was located. In the survey the influence on HDD

Table 4
The values assessing occurrence and severity of human and equipment based failures in HDD technology

Symbol of the fault	Category	Fault	Survey results – frequency of occurrence (%)	Occurrence in FMEA scale (O)	Survey results – severity	Severity in FMEA scale (S)
F1	Human	Incorrect calculations of loads and stresses that exceed the product pipe capacity during the pullback	7.19	7	2.7	5
F2	Human	Omitting to consider the allowable bending radius of the drill pipes or product pipe	10.43	7	2.9	6
F3	Human	Inappropriate choice of the external pipe coating	8.77	7	2.0	4
F4	Human	Downtime in the HDD process	17.55	8	2.4	5
F5	Human	Drill rig operator lacking the required skills	5.95	7	3.6	7
F6	Human	Fatigue of HDD crew	7.71	7	2.6	5
F7	Human	Lack of adequate supervision	5.00	7	2.9	6
F8	Human	Improper pipe connections: faults in fusion/ welding of pipes	2.43	6	3.1	6
F9	Human	Product pipe damage due to the exceeded installation loads	4.61	6	3.2	6
F10	Human	Not testing water for the drilling fluid preparation	9.48	7	2.0	4
F11	Human	Not testing the mud properties	8.23	7	2.5	5
F12	Human	Low quality of the material (pipes, bentonite)	7.53	7	3.1	6
F13	Human	Delay in the materials delivery and transportation	6.10	7	2.3	5
F14	Human	Problems with obtaining the building permission	7.81	7	1.3	3
F15	Human	Accidents on the construction site	2.26	6	2.0	4
F16	Equipment	Loss of communications with the drill rig	6.64	7	2.2	4
F17	Equipment	Drill pipe failure due to the material's fatigue	7.33	7	3.3	7
F18	Equipment	Drill rig failure	9.91	7	2.9	6
F19	Equipment	Mud motor failure *	6.50	7	3.0	6
F20	Equipment	Mud cleaning system failure *	6.50	7	3.2	6
F21	Equipment	Roller blocks failure*	5.22	7	1.5	3
F22	Equipment	Roller cradles failure*	2.24	6	1.6	3
F23	Equipment	Side cranes failure *	3.69	6	2.1	4
F24	Equipment	Ballasting system failure *	3.40	6	2.8	6

*if applied

failure was assessed using the following 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 (Table 2) by multiplying the original score obtained from the analysis of the survey results by 2 and rounding the result to the whole unit.

Identification of detection possibilities of faults in HDD technology and their assessment

Detection in this work is understood as actions aiming to find out early or discover a certain failure (so they can be classified as risk cause reduction in risk treatment). There are not included any actions aiming to stop the failure which has already occurred (e.g. risk effect reduction, risk transfer and risk elimination), as such actions cannot be classified as detection.

Table 5 presents the actions aiming to detect failures in HDD technology and the proposed values assessing difficulties of detection of failure modes (D). The proposed values assessing difficulties of detection of failure modes (D) are based on own analyzes supported by the conversations with HDD specialists.

As it can be seen from the last column in Table 5, improper choice of the external pipe coating, downtime in installation and mud cleaning system breakdown have the lowest detection possibilities (5 points in the FMEA scale).

Table 5
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)
F1	• Checking the correctness of the calculations of the designer using the appropriate computer program (e.g. Horizon, HDD Designer, D-Geo Pipeline, Driller, DrillPath, DrillMud, DrillEst, PPI Calculator, and FieldCalc System in relation to the selected equipment by the competent specialist • Considering installation failure mechanisms in the risk analysis in the drilling plan • Checking design company references from similar projects that have been carried out so far	2
F2	• The use of appropriate guidelines and appropriate computer programs to check the previously designed HDD drilling trajectory in combination with tension and torque expected on the pipe, in relation to the selected equipment by the competent specialist (the example computer programs that could be used are: DRILLER, HDD Designer); employing the competent specialist • Checking design company references for similar projects that have been carried out so far	2
F3	• An assessment of the expected geological conditions should be used to determine the most appropriate coating for the pipe • Checking if 2 coating on the pipe were designed: Corrosion protection and erosion protection. The erosion coating is there to protect the corrosion coating and if the erosion coating comes out of the hole with 0.001mm left and the corrosion protection coating is ok then it has done its job • Applying poroscope to check the condition of the pipe's insulation during the pullback • Carrying out a visual inspection of the pipeline before pulling back • Selection of certified suppliers and materials, • Consideration of crack and gouge allowance HDPE pipelines	5
F4	• Prediction of the previously realized installation delay based on its size risk level and an appropriate preparation of the work schedule taking it into consideration • Checking if there were any delays indicated in the references of the contractor from similar projects that have been carried out so far	5
F5	• Checking the contractor's experience in carrying out a similar project and references • Checking the drill rig operator' certificates from specialist trainings • Checking if there is appropriate supervision and highly specialized consulting at the construction site • Checking the type of drill rig type (the use of drilling rigs with full automation of the process allows to avoid operator's mistakes) • Checking if augmented reality is applied in the project to increase the drill rig operator's awareness of underground utilities	3

F6	• Assessment of the education and skills of the HDD crew, the number of working hours • Proper supervision at the building site (checking the certificates, references)	2
F7	• Proper supervision at the building site (checking the certificates, references) • Checking the supervisor certificates from specialist trainings	2
F8	• Proper supervision at the building site (checking the certificates, references) • Applying welding check procedures • Carrying out pressure test before installation	2
F9	• Using strain gauge or a load cell to measure the stress that the pipe is subjected to during the pullback together with establishing limits above which the driller should not go	2
F10	• Proper supervision at the building site (checking the certificates, references of the mud service)	2
F11	• Proper supervision at the building site (checking the certificates, references of the mud service)	2
F12	• Checking the certificates and references of suppliers and materials	2
F13	• Checking the certificates and references of suppliers and materials, • Proper project planning using dynamic and updated scheduling programs	2
F14	• Checking which permissions are required, • Checking the average time required to obtain all permissions, • Employing an experienced consultant to verify if the permission procedures were properly planned	2
F15	• Checking if there is appropriate supervision and highly specialized consulting at the construction site, • Checking the validity of Occupational Health and Safety certificates of workers.	3
F16	• Identification of a passive and active disturbance sources; temporarily disabling the source of interference if possible or choosing a steering system insensitive to a certain type of interferences • Pre-start checks (checking batteries and their operation time, the type of wire protective jackets, the condition of the wire, the correctness of drilling tools selection and tools damping vibrations in relation to the anticipated ground conditions, the condition of transmitter's insulation, checking completeness of the system elements (e.g. spiders, stabilizers)	3
F17	• Using Non Destructive Testing of HDD drill rods, such as Visual inspection (VTI), API/RSC thread inspection (API-TI), Dimensional inspection (DI), Electromagnetic tubular inspections (EMI), Magnetic particle (MT), Liquid dye penetrant (PT), Ultrasonic inspection of rotary-shouldered connections (UT-RSC), Ultrasonic inspection of high-stress areas and tube upsets (UTEA) • Defining stress limits based on the type and material of the drill pipe, establishing tension and torque limits, defining drilling radii and deviations • Carrying out Geotechnical investigation at the planning stage to determine the type of equipment needed	3

F18	• Pre-start checks- testing raise (testing rig rotation, rig crosshead movement, rig slow and fast up and down, pipe loader grip close and open, pipe loader swing and tilt, emergency stops, indicator lights, components move freely, if correct pressures are attained, computer readings) • Checking the documents from regular inspections and their dates and results • Checking if the drill rig was previously repaired and if original spare parts were used • Checking the type of drill rig protection system against failures (remote machine diagnostics on site in the case of applying new generation drilling rigs with displayed error messages)	3
F19	• Checking the documents from regular inspections and maintenance, their dates and results. • Testing on site (pre-starts checks) • Checking if the use mud motor components that have elastomeric elements are new. If they have already been used for one downhole trip they may be unsuitable due to the fact the content of oils, diesel, and other organic fluid additives makes the predictable run life of the elastomeric elements difficult to determine • Predicting mud motor wear during the drilling taking into consideration soil grain-size distribution, sand content in the drilling fluid (solids coming back to the bore hole cause wear of the mud motor) and the fluid density (too dense drilling fluid causes quicker wear of the elements of the system)	4
F20	• Checking the documents from regular inspections and maintenance, their dates and results. • Pre-start checks • Predicting the recycling system wear during the drilling taking into consideration soil grain-size distribution, sand content in the drilling fluid (solids coming back to the bore hole cause wear of pumps) and the fluid density (too dense drilling fluid causes quicker wear of the elements of the system)	5
F21	• Pre-start checks • Checking the documents from regular inspections and maintenance, their dates and results	3
F22	• Checking the documents from regular inspections and maintenance, their dates and results • Pre-start checks	3
F23	• Checking the documents of regular inspections and maintenance, their dates and results • Pre-start checks	3
F24	• Checking the documents of regular inspections and maintenance, their dates and results • Pre-start checks	3

FMEA evaluation results for human and equipment risk factors in HDD technology

Table 6 presents the evaluation results for HDD technology (Occurrence, Severity, Detection, Risk Priority Number and Priority).

In order to divide human and equipment based risk factors in HDD technology according to their contribution into cumulative Risk Priority Number, Pareto–Lorenz analysis was carried out. Figure 2 shows Pareto–Lorenz chart of RPN for human- and equipment based failures in HDD technology. Based on the results of the Pareto–Lorenz analysis, individual causes can be assigned to groups A, B or C. Group A should contain the failures which elimination is crucial for reducing the risk in the analyzed technology. Group B should contain failures which significance is secondary. Group C should contain the failures which, if eliminated, cause the least reduction in the risk in the analyzed technology. In the analyzed case, there is a clear difference in the groups. of causes (A, B, C) taking into account the criterion of the number of causes and the criterion of the effect value. The Lorenz curve obtained as a result of the analysis is in its initial phase flatter than the standard Lorenz curve.

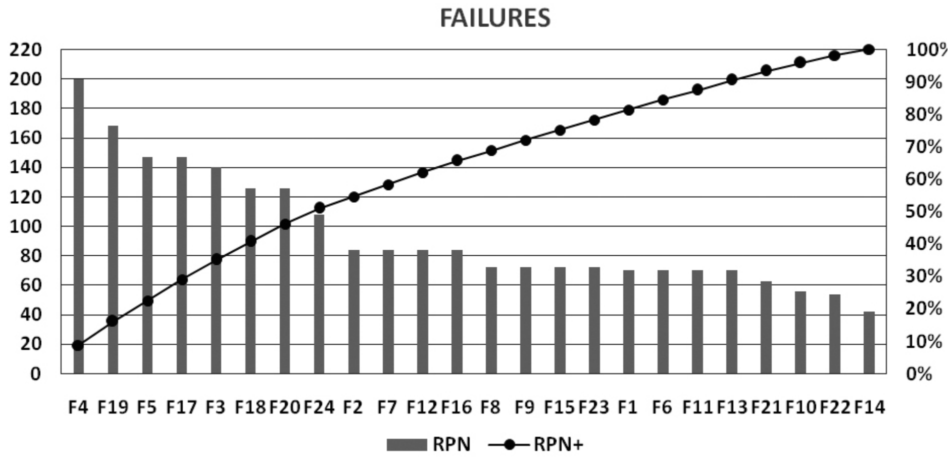

Fig. 2. Pareto–Lorenz chart of RPN for human- and equipment-based failures in HDD technology

Table 6
The evaluation results for human and equipment risk factors in HDD technology (Occurrence, Severity, Detection, Risk Priority Number and Priority)

Failure symbol	Occurrence (O)	Severity (S)	Detection (D)	RPN	Priority
F1	7.00	5.00	2.00	70.00	9
F2	7.00	6.00	2.00	84.00	7
F3	7.00	4.00	5.00	140.00	4
F4	8.00	5.00	5.00	200.00	1
F5	7.00	7.00	3.00	147.00	3
F6	7.00	5.00	2.00	70.00	9
F7	7.00	6.00	2.00	84.00	7
F8	6.00	6.00	2.00	72.00	8
F9	6.00	6.00	2.00	72.00	8
F10	7.00	4.00	2.00	56.00	11
F11	7.00	5.00	2.00	70.00	9
F12	7.00	6.00	2.00	84.00	7
F13	7.00	5.00	2.00	70.00	9
F14	7.00	3.00	2.00	42.00	13
F15	6.00	4.00	3.00	72.00	8
F16	7.00	4.00	3.00	84.00	7
F17	7.00	7.00	3.00	147.00	3
F18	7.00	6.00	3.00	126.00	5
F19	7.00	6.00	4.00	168.00	2
F20	7.00	6.00	3.00	126.00	5
F21	7.00	3.00	3.00	63.00	10
F22	6.00	3.00	3.00	54.00	12
F23	6.00	4.00	3.00	72.00	8
F24	6.00	6.00	3.00	108.00	6

When carrying out Pareto analysis in terms of the number of causes (types of failures), it can be seen that:

- 29% of causes (failures) generate 46% of effects (RPN+),
- next 21% of causes (failures) generate 20% of effects (RPN+),
- the remaining 50% causes (failures) generate 34% effects (RPN+).

When carrying out Pareto analysis in terms of the value of failure effects (RPN+):

- 54% of causes lead to 69% of effects (RPN+),
- next 33% causes lead to 24% effects (RPN+),
- the remaining 13% causes lead to 7% effects (RPN+).

Assuming that group A should include causes constituting up to 30% of failure types, this group should include such failures as F4 (downtime in the HDD process), F19 (mud motor failure), F5 (drill rig operator lacking the required skills), F17 (drill pipe failure due to the material's fatigue), F3 (inappropriate choice of the external pipe coating), F18 (drill rig failure) and F20 (mud cleaning system failure).

Assuming that group A should include failures generating up to 70% of all effects (RPN+), the group indicated above should be extended to F24, F2, F7, F12, F16 and F8. Due to the fact that the main purpose of the analysis is to identify the most significant types of failures, the effect value criterion (RPN+) should not be taken uncritically into account. The criterion of the number of types of failure would be more interesting in the analyzed case.

All in all, the study has shown that the most critical risk factors, assigned to group A were: F4, F19, F5, F17, F3, F28 and F20. The risk factors assigned to group B were: F24, F2, F7, F12 and F16. Among risk factors with the lowest RPN (group C) were: F8, F9, F15, F23, F1, F6, F11, F13, F21, F10, F22 and F14.

Summary

In this work a new risk evaluation model dedicated for HDD technology was presented, in which Failure Mode and Effect Analysis with Pareto–Lorenz analysis was applied to evaluate human and equipment risk factors. It is dedicated particularly for HDD projects with a modest budget, in which a group of experts could not be involved in risk assessment process. Moreover, it can be also very useful for preliminary human and equipment risk evaluation for bigger and more complex HDD projects. In this work 60 detection possibilities of human and equipment based failures in HDD technology were proposed, deeply analyzed, identified and evaluated. Such investigation of detection is very valuable for risk management of all projects carried out using HDD technology, as properly applied detection actions are almost always significantly cheaper and less troublesome than treating risk after unwanted event occurrence. The proposed approach allows to take into account the severity of the risk factor and the possibility of detecting faults, which were not plainly separated and analyzed in the previous works. Such an approach enabled to rank HDD failures and identify the most critical risks. The study revealed that the most critical human and equipment risks were: F4 (downtime in the HDD process), F19 (mud motor failure), F5 (drill rig operator lacking the required skills), F17 (drill pipe failure due to the material's fatigue), F3 (inappropriate choice of the external pipe coating), F18 (drill rig failure) and F20 (mud cleaning system failure). For those risks it is especially important to search for new detection techniques or risk treatment possibilities other than risk cause reduction, such as risk effect reduction, risk transfer, risk elimination or active risk retention.

It was found out that two different events have similar RPN value (e.g. RPN(F10) = 56 and RPN(F22) = 54), but they have diverse interpretations and various semantic risk implications. F10 has higher risk than F22, although its possibilities of detections were higher than for F10. It is caused by different values of occurrence and severity. In extreme cases, it could lead to ignoring or underestimation of a high-risk event, which occurrence may generate high costs. Moreover, it may happen that not all of actions aiming to detect failures, which were proposed in Table 5, will be applied in a certain HDD project. In such a case, the detection value suitable for that project would differ from that stated in Table 5, as all detection values in this work were proposed based on the assumption that all of them will be used in the project. In such a case, it is advised to individually assess the detection possibilities based on information from Table 5. It would allow to individually measure the effectiveness of the detection actions which are planned to be used in a certain project.

The main limitation of FMEA method in the aspect of HDD include the fact that the ranks for probability and severity of faults are based on statistical approach (survey results) and although they correctly illustrate the statistical view of faults and are satisfactory for preliminary risk evaluation for many HDD projects, they may not be appropriate for each specific HDD project. It may cause that the risk evaluation may not be always accurate, especially in a case of specific HDD projects, which statistically differ from typical HDD projects in terms of e.g. really challenging ground conditions, length and diameter of the built-in pipeline.

Further research is oriented in developing a new risk assessment model for HDD technology, in which machine learning will be applied to eliminate the need to involve a group of experts into the risk assessment process.

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