Tunnelling and Underground Space Technology 43 (2014) 67–77

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Trenchless Technology Research

The quantitative risk assessment of MINI, MIDI and MAXI Horizontal Directional Drilling Projects applying Fuzzy Fault Tree Analysis

Maria Gierczak *

Faculty of Environmental Engineering, Geomatics and Power Engineering, Kielce University of Technology, Al. 1000-lecia Państwa Polskiego 7, 25-314 Kielce, Poland

ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form 11 March 2014
Accepted 4 April 2014
Available online 9 May 2014

Keywords:
HDD technology
Qualitative risk assessment
Quantitative risk assessment
Fault Tree Analysis
Fuzzy sets

ABSTRACT

The risk level of the HDD project is a key parameter when assessing the project feasibility and making the project pricing. It is also a starting point for introducing the risk management strategy which aims to reduce the number of installation failures and their negative consequences. The objective of this work was to develop a new mathematical model for the qualitative and quantitative risk assessment of HDD projects of various sizes (MINI, MIDI and MAXI), which allows to consider the installation specificity (the optional possibility of applying various tools and machines). The risk assessment was carried out applying the Fuzzy Fault Tree Analysis. The unwanted events were divided into 4 classes: problems with the ground, machines, environment and management. Applying the fuzzy set theory in the proposed model made it possible to decrease the uncertainty, the lack of precision and the difficulties with gaining the crisp values of the basic events probability, which occur in the conventional Fault Tree Analysis. The practical application of the proposed model for the MINI, MIDI and MAXI HDD projects was shown on four examples.

1. Introduction

The objective of this work was to develop a mathematical model for the quantitative and qualitative risk assessment for the installation of underground utilities using Horizontal Directional Drilling (HDD) technology. HDD technology is used to install water, gas, heating, drain, sewers pipes and cables under obstacles such as rivers, busy streets, highways, airport runways, areas congested with buildings or underground utilities, and environmentally sensitive areas. The analysis of the risk factors for such investments and their mathematical description are included in the aim of this work.

Many contractors who install underground utilities applying HDD technology are not able to carry out risk assessment in the project planning phase, as they do not have any mathematical model which allows to do it for various sizes of HDD installations. The contractors emphasize the necessity of risk assessment before starting the realization of the investment, as the estimation of the risk level is the starting point to analyze the project feasibility and cost estimation. Thanks to carrying out a risk assessment, a lot of serious economic and legal consequences connected with HDD failure e.g. the damage of other existing underground utilities, the damage of expensive HDD down-hole equipment, the damage to the installed pipeline, etc. can be avoided. Currently, there is also no risk management strategy available, which could be an effective tool to reduce the risk level.

In (Woodroffe and Ariaratnam, 2008) the authors suggested using the total risk index model as a guide for the overall risks of an urban utility project. The following sub indexes were analyzed: a contingency plan, the determining bid price, the eco-social factors and consideration factors. Recently papers (Abdelgawad et al., 2010; Ma et al., 2010) have appeared in literature in which the authors tried to carry out the risk assessment for HDD installations. In (Abdelgawad et al., 2010), the authors evaluated quantitatively and qualitatively the risk on the example of one HDD installation. This model did not take into consideration some of the risk factors which have a significant influence on the total risk level (such as: various design mistakes, the downtime in installation, the unexpected natural and man-made obstacles, various problems with HDD construction works, problems with supply, materials, quality, the legal conditions and economic problems). In (Ma et al., 2010) the authors suggested a model for the risk assessment only for MAXI HDD projects, applying the Analytical Hierarchy Process and the Fuzzy Comprehensive Evaluation Method. In this work the risk factors were not developed to a sufficient level of detail, therefore when carrying out the risk assessment of a particular element, some important components may be missed and the final risk level may be incorrect. The Analytical Hierarchy Process is said to be controversial, as the decision-maker preferences are characterized by the relative

* Tel.: +48 413424465.
E-mail address: maria.gierczak@gmail.com

http://dx.doi.org/10.1016/j.tust.2014.04.003
0886-7798/

importance assessment of the sub criteria of all the hierarchy levels. Both of the presented models did not allow to consider the project specificity (the optional possibility of applying various tools and machines). In (Shahriar et al., 2007) the fundamental of risk classification and mitigation in mechanized rock tunneling were presented. The main geotechnical hazards and some important mitigation measures were shown. It was emphasized that that risk assessment stages and the effect of risk mitigation measures are very important elements during the early engineering phase.

In the literature no risk assessment model for HDD technology was found, which takes into account the risk management strategy. It indicates the need to develop a new mathematical model for the risk assessment in HDD technology, taking into consideration the important risk factors, the installation specificity (the optional possibility of applying a mud cleaning system, mud motor, ballasting system, roller blocks, roller cradles and side cranes) and the possibility of including the risk management strategy. That is why it is important to discuss the problem of risk assessment again and take into consideration a number of additional risk factors which have not been considered so far. Moreover, the proposed model is aimed to be applied to HDD installations of various sizes, namely MINI HDD, MIDI HDD and MAXI HDD. For any of the presented models described in the literature so far it is improper to apply for each size of installation, namely the model suggested in (Abdelgawad et al., 2010) would be better for MINI HDD, and the model suggested in (Ma et al., 2010) could be applied only for MAXI HDD installations.

In the conventional approach to solving the fault tree (FT), the probability theory is used. The crisp values of the basic events probabilities must be known. In practice, it is very difficult and sometimes even impossible to get crisp values of the basic events probabilities for HDD projects. Even when the crisp values of probabilities are obtained, HDD experts, who assessed the probabilities indicated that they are imprecise, deficient and vague, because the basic events are not stationary and there is often the lack of sufficient data to estimate the crisp probabilities of the basic events. Applying the conventional approach to solving FT may lead to gaining insufficient information in the risk analysis or increasing the uncertainty of the analysis. To overcome those difficulties, the Fuzzy Fault Tree was employed in this work. Fuzzy based solutions techniques allow to generate the basic events failure probabilities even when we are able to obtain only a little quantitative information. The fuzzy sets theory and possibility theory, which are used in Fuzzy Fault Tree Analysis, allowed to deal with ambiguous, inaccurate and quantitatively incomplete information. The linguistic terms (very low, low, medium, high and very high) were applied in this work to assess the probability of the individual basic events occurrence. Applying the fuzzy sets theory allowed for a gradual transition between the linguistic terms.

2. The proposed methodology for the risk analysis of the HDD projects

The research was divided into two parts: the development of the new mathematical model for the qualitative and quantitative risk assessment for HDD projects and the development of the risk management strategy for HDD. The proposed methodology for the risk analysis of HDD projects, includes 8 steps and is shown in Fig. 1.

2.1. Step 1: Definition of the analysis scope

The aim of the analysis is to assess the risk level for a trenchless pipe laying project applying HDD technology.

2.2. Step 2: Gathering information about various HDD projects and their potential problems

The potential hazards in HDD projects were identified thanks to the analysis of the expert surveys, which were carried out in 5 different countries, the information gathered during the meetings with the experts representing the manufacturers of the HDD rigs, drill rods, steering systems, drilling fluids, product pipes, as well as the interviews with the experienced contractors. Some observations of various HDD installations also supported the identification of potential problems in the HDD projects.

2.3. Step 3: Hazard identification

As many as 17 failure scenarios in HDD and their consequences were described in (Gierczak, 2013). The top event was defined as the occurrence of an unsuccessful HDD investment (the HDD failure not meeting the project objectives, exceeding the cost stated in the budget or the time assumed in the project schedule in the contract). The main intermediate events include: problems with the ground, the machines, the environment and management.

2.4. Step 4: Construction of the fault tree

The fault tree was drawn in a horizontal format, so the top event was placed at the top of the page, the basic and underdeveloped events at the bottom. 21 basic events and 1 underdeveloped were identified. An underdeveloped event is an event which is not further developed either because it is of insufficient consequence or because information is unavailable (NASA, 2002). The events concerning human error (the contractor's error in the analyzed FT) are often underdeveloped as they are the result from a number of various factors and it is not needed to analyze them in further detail. Modeling to too high a resolution (the level of detail) could result in obtaining enormous probabilities and increase the uncertainty of the analysis. The sequences of the events were connected with the logic gates. The fault tree was developed for such a level of detail, which allows to identify the functional dependencies and the relationship between the events. Fig. 2 shows the proposed FT for HDD projects. In Table 1 the basic and underdeveloped events with their most important consequences were presented. Some basic events need further clarification. In this work the downtime in the installation was understood as the downtime caused by the inaccessibility of equipment due to the delay in the previous HDD installation. The loss of communication with the drill rig was defined as a steering system failure, a flat battery, magnetic interference (active and passive), problems during drilling at greater depths, shorts in the wire, broken wires and steering problems due to the improper choice of drilling tools relative to the anticipated ground conditions. Drill tool failure due to the material's fatigue was understood to be such a failure which was not caused by the operator or a design mistake, as problems caused by the design mistake or the operator lacking the required skills were considered separately. Severe weather conditions were understood to be low temperatures, heavy rainfall or snowfall, strong winds which caused problems with bentonite systems, the drilling progress and the product pipe connections. Because of the fact that MIDI and MAXI HDD projects require very high financial expenses connected with using large amounts of materials, it is important to consider one additional basic event for those investments, namely improper cost calculations. The high costs of MIDI and MAXI HDD installations also arise from the long period of realization of those projects, the highest complexity of the task and the need to employ expensive equipment (MAXI rigs, steering systems), which are often purchased in foreign currency.

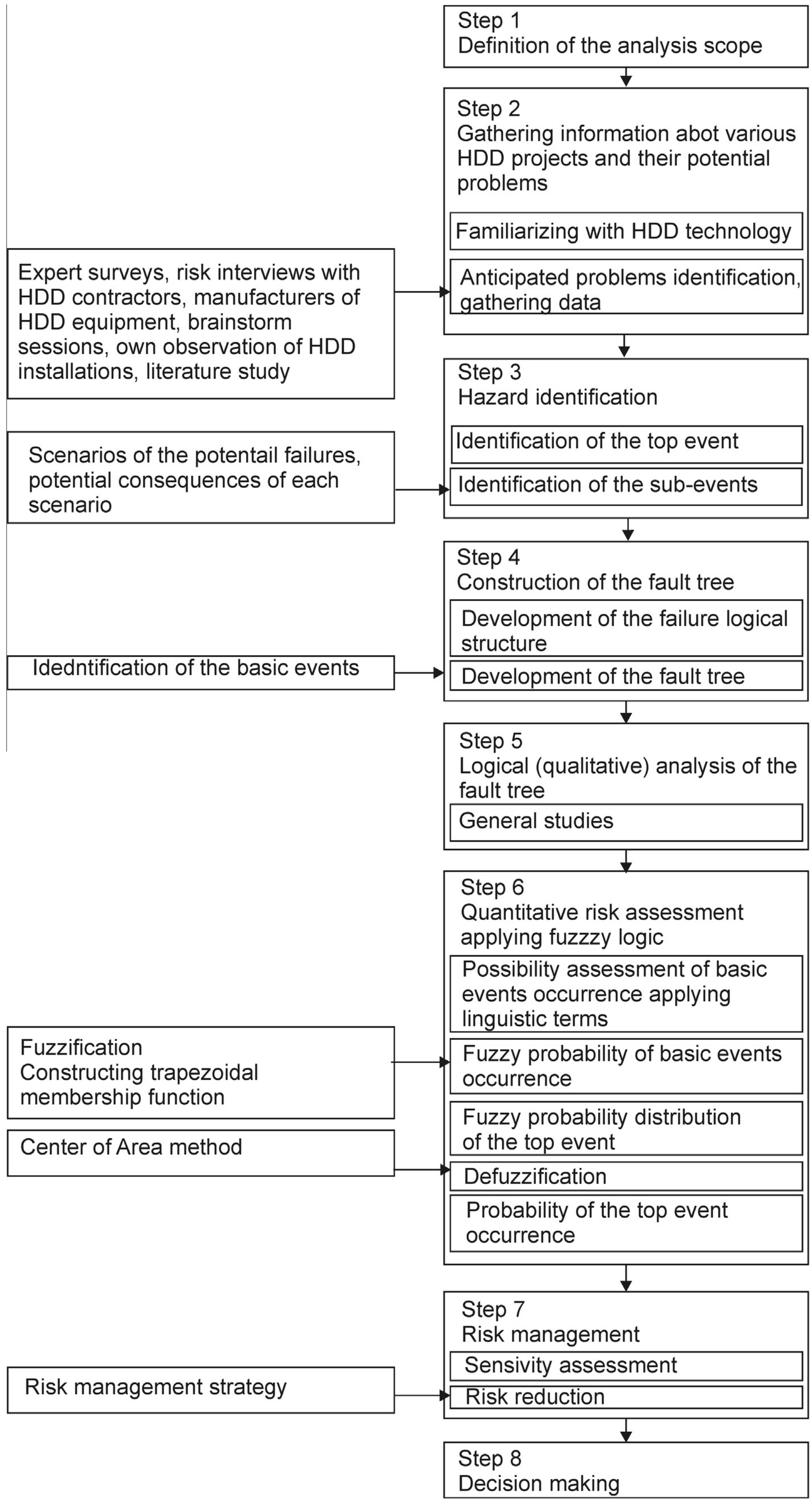

Fig. 1. The proposed methodology for the risk analysis of HDD projects.

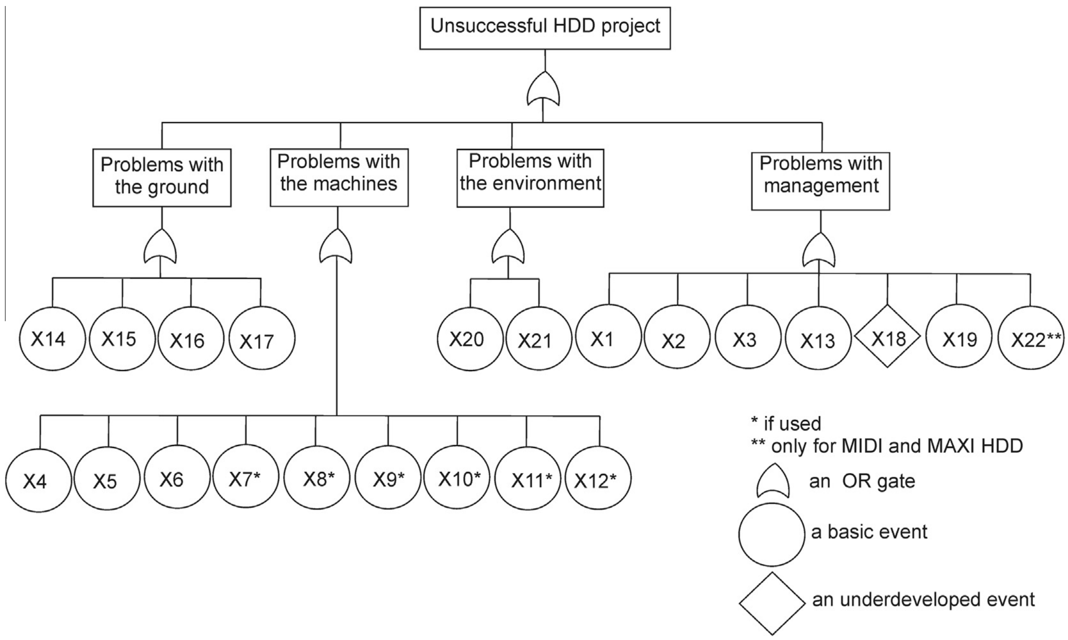

Fig. 2. The proposed FT for the risk assessment for MINI, MIDI and MAXI HDD projects.

2.5. Step 5: Logical (qualitative) analysis of the fault tree

The logical analysis (qualitative) of the fault tree was carried out applying the methodology of general FT studies, because in the FT structure there are only OR gates and identical events do not occur on separate FT branches.

2.6. Step 6: Quantitative risk assessment applying fuzzy arithmetic

In (Zadeh, 1965) a theory was introduced in which objects – fuzzy sets – are sets with imprecise boundaries. The membership in a fuzzy set was considered to be a matter of degree rather than affirmation or denial. If A is a fuzzy set and p is a relevant object (probability), the statement “p is a member of A” is not necessarily either true of false (as it is in crisp set theory, where two-value logic is used), but can be true to some degree. This degree is called the degree (grade) of membership. The membership degree $\mu_A(p)$ quantifies the grade of membership of the element p to the fuzzy set, so it is the degree to which elements p are compatible with the linguistic term, that we want to represent by a fuzzy set. For example $\mu_A(p) = 0$ means that the analyzed element p is not a member of the fuzzy set, $\mu_A(p) = 1$ means that it fully belongs to the fuzzy stet and all intermediate values $0 < \mu_A(p) < 1$ mean that element p belongs to the fuzzy set partially. It provides a meaningful representation of measurement uncertainties and a significant representation of vague concepts, which are present in spoken language (Klir and Yuan, 1995).

The top event probability in HDD projects cannot be calculated accurately using the classical probability theory, as the basic events in HDD projects are not stationary and there is not enough historical data available to assess the crisp failure rates of the system components, which are deficient, imprecise and vague in practice. The fuzzy sets allow a gradual transition between the linguistic terms.

The linguistic terms are used in spoken language, which uses the possibility theory, that is based on the fuzzy sets theory. The experienced experts in HDD when describing the probability of occurrence of the basic events in HDD often prefer to use the linguistic terms, which are based on a more intuitive model, based on years of experience, expertise, practical skills and the observation of many various cases in HDD. In many cases they are unable to give crisp values of probability. In this work the linguistic terms were applied to assess the probability of the individual basic events occurrence. A group of HDD experts was asked to assign one linguistic term to each basic event. Particular care was drawn to the proper choice of the experts. They were HDD contractors with many years of experience in HDD operations of a particular size. The installation specificity was also taken into consideration when choosing the experts. The group of experts was familiar with the project details and specifications. The following linguistic terms were used to describe the probability of the basic events occurrence:

- very low,
- low,
- medium,
- high,
- very high.

The experts were firstly asked to express the probability of basic events occurrence using the above mentioned linguistic terms. In order to construct the membership function, the experts were asked to define the meaning of each linguistic term, that is to assign to each value of probability ($p \in P$) a membership grade $\mu_A(p)$, that, according to their opinion, best captures the meaning of the linguistic term, which is represented by the fuzzy set A.

However, it is often difficult or not feasible to define the membership function that adequately captures a given linguistic term. In this work, the task was facilitated by asking the group of experts a question: “which elements p have the degree $\mu_A(p)$ of membership in a fuzzy set A” (Klir and Yuan, 1995). The answers allowed to receive a set of pairs $\langle p, \mu_A(p)\rangle$, which were used to construct a membership function of a trapezoidal shape, that is often used in the description of the problems connected with safety. The trapezoidal membership function is defined by the formula (1):

$$\mu_A(p) = \begin{cases} 0 \ when \ p_i < p_a \ and \ p_i > p_d \\ \frac{p_i - p_a}{p_b - p_a} \ when \ p_a \leqslant p_i < p_b \\ 1 \ when \ p_b \leqslant p_i \leqslant p_c \\ \frac{p_d - p_i}{p_d - p_c} \ when \ p_c < p_i \leqslant p_d \end{cases} \tag{1}$$

Table 1
Basic and underdeveloped events with their most important consequences.

The event symbol	The event name	The most important consequences
X1	Improper calculations of loads and stresses that exceed the product pipe capacity during the installation	– taking incorrect assumption of the HDD process parameters (e.g. too high pulling force), – product pipe damage during the installation, see also the consequences of X3, – improper choice of the drill rig, which will not have parameters allowing to complete the drilling, – additional costs connected with bringing new machines which would be able to complete the task, – delay in installation
X2	Not taking into consideration the allowable bending radius of drill pipes or the product pipe	– drill pipe or product pipe damage due to overstressing, see also the consequences of X3 and X5, – leaving expensive drilling tools or product pipe underground or under the crossed obstacle
X3	Improper choice of the external pipe coating	– damage to the product pipe coating or product pipe, – additional costs connected with buying a new product pipe and restarting the installation, – delay in installation
X4	Loss of communications with the drill rig	– no possibility of steering, – not precise steering, – additional costs connected with bringing additional (in working order) steering system or spare parts, – delay in installation
X5	Drill tool failure due to the material's fatigue	– no possibility of completing the installation, – need to retract the drill pipes and replace the damaged drilling tool, – leaving expensive drilling tools or product pipe underground or under the crossed obstacle, – additional costs connected with bringing additional tools (in working order), – delay in installation, – need to start a new bore
X6, X7, X8, X11, X12	Drill rig break down, Mud motor breakdown*, Mud cleaning system breakdown*, Side cranes breakdown* Ballasting system breakdown*	– no possibility of completing the project unless another (in working order) equipment or spare parts are brought, – additional costs connected with bringing additional equipment (in working order) or spare parts, – delay in installation, – product pipe failure due to product pipe fall from height (in the case of side cranes failure), see also the consequences of X3
X9, X10	Roller blocks failure*, Roller cradles failure*	– increase of friction during the product pipe pulling, – product pipe failure, see also the consequences of X3
X13	Downtime in the installation due to unavailable equipment	– delay in starting the installation due to unavailable equipment because of the delay in completing the – previous realized installation, – economic loss
X14	Unexpected natural or man-made subsurface obstacles	– failure of the drilling tools or the product pipe (see also the consequences of X3 and X5), – striking or damaging existing utilities, – lower penetration rates, – delay in installation
X15	Bore hole collapse	– no possibility of the installation progress, – additional costs connected with pushing or pulling the tools or product pipe out of the bore, – need to install the product pipe again, – additional costs connected with buying special drilling fluid additives which prevent bore hole collapse, – increase of the thrust or pullback pressures, – decrease or preventing drilling fluid circulation, – delay in installation
X16	Blocking of the drilling pipe or product pipe installation due to the swelling of clay and silt	– no possibility of the installation progress, – delay in installation, – additional costs connected with the retrieving a stuck drill rod or product pipe, – additional costs connected with buying special drilling fluid additives which prevent swelling of clay and silt, – drill pipe failure (see also the consequences of X5)
X17	Drilling fluid seepage	– no possibility of the progress of the installation, – delay in installation, – additional costs connected with pushing or pulling the tools or product pipe out of the bore, – additional costs connected with buying special drilling fluid additives which prevent drilling fluid seepage
X18	Contractor's error	– faulty product pipes' connections, – not testing properties of water used for drilling fluid preparation or mud properties, – product pipe damage due to exceeding the allowable installation loads, see also the consequences of X3, – delay in installation
X19	Problem with supply and quality	– delay in installation, – low quality of materials and problems connected with it (see also consequences of possible problems caused by using low quality drilling fluids and additives X15, X16, X17)
X20	Legal problem	– no possibility of starting the installation because of the lack of the needed permissions,

(*continued on next page*)

Table 1 (*continued*)

The event symbol	The event name	The most important consequences
X21	Severe weather conditions	– problems connected with claims concerning bothersome noise emission or the damage to existing underground and surface utilities – frozen machines, – equipment failures due to severe weather conditions (see also the consequences of X6, X7, X8, X11, X12), – improper joints of the product pipe due to strong wind, rain or snow, – product pipe failure due to too low temperatures or exposure to the sun, see also the consequences of X3, – delay in installation
X22	Improper cost calculations for the investment**	– loss

* If used.
** Only for MIDI and MAXI HDD.

The trapezoidal membership function defined by the formula (1) was presented in Fig. 3.

In the proposed approach, each fuzzy set was defined using 4 points (Fig. 3) e.g. $A(p_a, p_b, p_c, p_d)$, where: p_a – the minimal value of the probability, $p_b \leqslant p_i \leqslant p_c$ – the most probable value of the probability, and p_d – the maximal value of the probability.

When p is in the interval $\langle p_b, p_c\rangle$, then its membership grade to the fuzzy set is 1, which means, that it is the most probable value of the data assessment. The residual constants $\{p_a, p_d\}$ are the lower and upper limits of the available data range. Those values reflect the data fuzziness. This is put into numbers in Fig. 4, which presents the membership function representing the concepts of very low, low, medium, high and very high probabilities of the basic or underdeveloped event occurrence for one group of experts. In order to define the membership functions which properly captures each linguistic term (very low, low, medium, high, very high), the group of experts was asked to exemplify it for some representative elements of p. In this way a set of pairs $\langle p, \mu_A(p)\rangle$ was received, e.g. for low probability $\langle 1,0\rangle$, $\langle 15,0\rangle$, $\langle 3,0.5\rangle$, $\langle 12.5,0.5\rangle$, $\langle 5,1\rangle$, $\langle 10,1\rangle$. Table 2 shows the factors determining the risk level for all identified events.

The occurrence of any of the basic or underdeveloped events in the proposed FT (Fig. 2) is sufficient to cause the top event occurrence. The fuzzy probability of each of the basic and underdeveloped events is read from the membership function for different values of the membership grade α with the step k.

In order to calculate the probability of the top event occurrence, the following formula can be used (2):

$$\widetilde{P_{t\alpha_{jk}}} = \left[1 - \prod_{i=1}^{n}\left(1 - \frac{\widetilde{P_{Xi_{\alpha_{jk}}}}}{100}\right)\right] 100\% \tag{2}$$

where $\widetilde{P_{t\alpha_{jk}}}$ – the fuzzy probability of the top event occurrence for the membership degree α_{jk} (%), $\widetilde{P_{Xi_{\alpha_{jk}}}}$ – the fuzzy probability of the basic or underdeveloped event Xi occurrence for the membership degree α_{jk} (%), α_{jk} – jk-th membership degree to the set of fuzzy probabilities defining each linguistic value, n – the number of basic or underdeveloped events connected with OR gates, $j = 0,1,2,\ldots,m-1$, m – the number of the analyzed membership grades, k – the step of changes of the membership grades to the fuzzy set $k = \frac{1}{m-1}$.

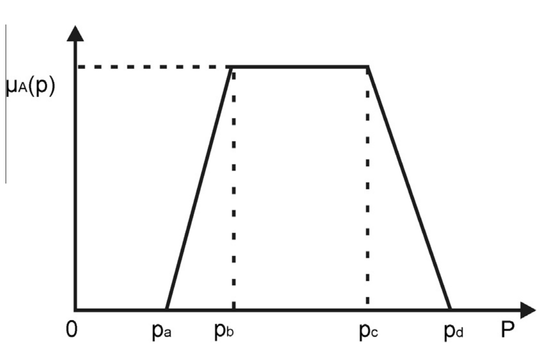

Fig. 3. The trapezoidal membership function defined by the formula (1).

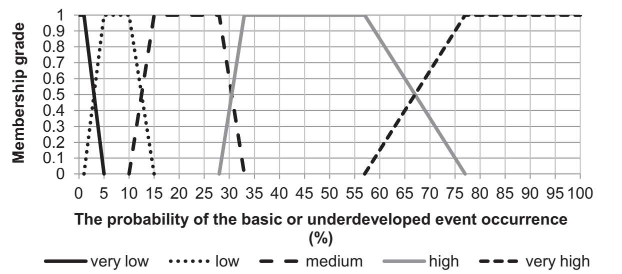

Fig. 4. The membership function for the probability of the basic or underdeveloped events occurrence for the MAXI HDD project in the West Pomeranian Voivodeship (group of specialists no. 3).

The fuzzy probability of the top event occurrence for the membership degree α_{jk} is defined by the formula (3):

$$\widetilde{P_{Xi_{\alpha_{jk}}}} = (\widetilde{P_{Xi_{a\alpha_{jk}}}}, \widetilde{P_{Xi_{d\alpha_{jk}}}}) \tag{3}$$

where $\widetilde{P_{Xi_{a\alpha_{jk}}}}$, $\widetilde{P_{Xi_{d\alpha_{jk}}}}$ – the extreme (from the left and high side) values of the fuzzy probability of the basic or underdeveloped event Xi occurrence, read from the trapezoidal membership function for the membership grade α_{jk} (%).

The extreme values of each event fuzzy probability are read from the membership function for values of α with the step k between each α. Substituting various values of fuzzy probability to the formula (2) for various values of membership grades α, the top event fuzzy probability is calculated for the following values of membership grade α. Based on the carried calculations, the fuzzy probability distribution graph for the top event can be developed.

The defuzzification process must be carried out in order to choose the right value of top event probability from the fuzzy set. The Center of Area Method (also called the Center of Gravity Method or Centroid Method) was applied in the defuzzification process. The defuzzification process is the operation of defining the crisp value of p, which would represent the set in the most reliable way (Yager and Filev, 1994).

The probability of the top event occurrence, called shortly the defuzzified value can be calculated from the formula (4):

$$P_t^{COA} = \frac{\sum_{j=0}^{m} \widetilde{P}_{ta\alpha_{jk}} \cdot \alpha_{jk}}{\sum_{j=0}^{m} \alpha_{jk}} + \frac{\sum_{j=0}^{m} \widetilde{P}_{td\alpha_{jk}} \cdot \alpha_{jk}}{\sum_{j=0}^{m} \alpha_{jk}} \tag{4}$$

Table 2
The factors determining the risk level for all the identified events.

The event symbol	The factors determining the risk level
X1, X2	– the experience and reliability of the design company, – the applied software and calculating methods
X3	– the geotechnical conditions and the type of chosen pipe coating (in the case when the drilling is carried out in postindustrial areas, there is a higher risk of a product pipe failure due to the contact with boulders or sharp objects in the ground)
X4	– the type of applied steering system (in the case of the walkover systems and wireline steering systems, there is a risk of the presence of passive and active interferences, e.g. power lines, traffic loops, fiber trace lines, invisible dog fences, metal structures, rebar, salt water and minerals in the ground. The presence of such interferences in the area of the building site and neighborhood can result in false signal readings, false readings of depth, inclination loss, blocked information and wrong calibration (Willoughby, 2005), – the ground conditions (the risk increases in the case of: • drilling in rock formations due to the shock loads and possible transmitter vibrations, • drilling in abrasive soils, rocks or cobbles due to the large amount of heat transfer from the drill head to the transmitter housing; • drilling in gravel and the grounds containing boulders, as then steering problems or unresponsive steering may occur) – the drilling depth in the case of applying the walkover systems (at depths more than 20 m the reading can be encumbered with errors (Kuliczkowski et al., 2010) – the time of the drilling and the battery capacity in the case of applying the walkover system (the possibility of running the battery down underground) – the type of crossing in the case of applying the walkover system (in the case of big rivers, rivers with a strong current, highways and railway crossings there is usually a need that the receiver should be positioned directly over the transmitter (Kuliczkowski et al., 2010)), – the borehole length in the case of applying wireline systems (when the section is long, the wire is often broken) – the type of wireline coating in the case of applying the wireline system (the possibility of strikes) – limited space on the building site in the case of applying the wireline systems (the limited space for placing the wire only on short sections on the river banks or narrow sections on busy streets)
X5	– the operational term of the drilling tools, – the proper choice of the drilling tools relative to the anticipated geotechnical conditions, – the way of the maintenance of drilling tools and the precision of the periodical inspections, – whether the drilling tools were repaired previously and if original spare parts were used
X6	– the operational term of the drill rig and the way of its operational use, – the way of the maintenance of drilling tools and the precision of the periodical inspections, – whether the drilling tools were previously repaired and if original spare parts were used – the type of drill rig protection system against failures (the automatic supervision during standard operation)
X7, X8	– factors analogical as for X6 and soil grain-size distribution, sand content in the drilling fluid (solids coming back to the bore hole cause the wearing of the mud motor and pumps) and the fluid density (too dense a drilling fluid causes quicker wear of the elements of the system)
X9, X10, X11, X12	– factors analogical as for X6
X13	– the size of the previously realized installation and the assessed risk for that installation
X14	– the reliability and quality of the company providing geotechnical services, – the proper choice of the geotechnical investigations in comparison to the specificity of the installation, the size and type of the building site (e.g. in glacial areas, there are expected buried cobbles and boulders, in landslide areas there are the expected buried trees and other objects, in areas with meandering rivers with a low current there are the expected fine-grained deposits, in areas with meandering rivers with a fast current – boulders, in kartstic areas, areas with caves and springs, in areas of post-metallurgical dumps and mining areas there are the expected voids or caverns in the ground, in postindustrial and industrial areas - a higher risk of encountering man-made structures in the ground), – the number of site investigation methods used and their reliability
X15	– the ground conditions (risk increases in the cases, when: – the ground does not contain cohesive components, there is no natural cohesion of the grains, because the ground consists of pure sands, gravel or loose rock, – the size of the sedimentary grains is almost the same (homogenous grain-size distribution), – the ground contains oversize materials (cobbles and boulders), heavy, large grains that gravitationally fall to the bore hole bottom, e.g. if the ground contains materials > 76 mm – very high risk, more than 50% of materials 19 mm – high risk, 30–49% materials 19 mm – medium risk (Gelinas and Mathy, 2004))
X16	– the ground conditions (the content of clay fraction, its mineral composition, saturation ratio, humidity, soil grain-size distribution, content of exchangeable cations determining ground hydrophilicity, bulk density, overburden pressure (Gelinas and Mathy, 2004)). Risk connected with the swelling of the ground can be also assessed applying the chart, which provides an indication of the shrink-swell potential (Naval Facilities Engineering Command, 1986).
X17	– the ground conditions and the bore path design. Risk increases: – at considerable elevation differences between the entry and exit points or points along the alignment, – in areas situated along the alignment with the depth cover less than 12 m and in areas with significant changes in density or composition of ground conditions (ASCE, 2005), – at drilling in the clear, coarse-grained, permeable soils (e.g. in sands, Graves containing less than 12% of fine or in fractious rocks) (Gelinas and Mathy, 2004), – in areas where the HDD alignment is close to existing utilities located in backfills, which were filled with trench backfill materials, which act as a drainage for the drilling fluid (Gelinas and Mathy, 2004), – at strong groundwater inflow
X18	– the education and skills of the worker, the number of working hours, influencing their fatigue and the proper supervision
X19	– the choice of the certified, reliable suppliers and certified materials from known manufacturers
X20	– the situation of the building site (e.g. a situation close to environmentally sensitive areas such as wetlands, river banks, intermittent drainage channels, endangered plants, a wildlife habitat, a sensitive habitat or a housing estate is connected with the special requirements of noise emission), – the period of the drilling works (risk increases if it falls on the birds breeding season), – the type of applied machines (if they are equipped with a noise reduction system), – the early gaining of all the required permits, – the type of contract

(*continued on next page*)

Table 2 (*continued*)

The event symbol	The factors determining the risk level
X21	– the season and the specificity of the building site (low temperatures have a negative impact on: plastic pipe storage, the fusion process, the maintenance of the equipment; strong wind, heavy rainfall or snowfall have a negative impact on pipe connections.; in the case of project realization in close proximity to rivers, the risk is increased due to possible flooding or ice melting)
X22	– the way and the accuracy of the definition of the break-even point of the investment, the correctness of the cost planning, the type of contract, the inflation rate, the interest rate, the imbalance of exchange rates

where P_t^{COA} – the defuzzified value (the top event probability of occurrence) (%), $\widetilde{P_{ta\alpha_{jk}}}$ – the extreme (from the left side) values of the top event for jk-th membership grade (%), $\widetilde{P_{td\alpha_{jk}}}$ – the extreme (from the right side) values of the top event for jk-th membership grade (%), $j = 0, 1, 2, \ldots, m - 1$, m – the number of the analyzed membership grades, k – the step of changes of the membership grades to the fuzzy set $k = \frac{1}{m-1}$, α_{jk} – jk-th membership grade to the set of fuzzy probabilities of the top event occurrence.

The exit F of the fuzzy system is a fuzzy subset of the real straight line. For $p_{jk} \in P$, $F(p_{jk}) = \alpha_{jk}$ shows in which grade each probability fulfills our criteria and expectations. The defuzzification algorithm uses F to choose the best value of the fuzzy system exit P_t^{COA}. The defuzzification defines the strategy of using the fuzzy subset F to choose one element representing set P (see formula 4).

Steps 7 and 8 (risk management and decision making) will not be discussed in this work due to their ampleness and will be described in future works.

3. Examples of application

The risk assessment of 10 various HHD projects was carried out applying the proposed methodology described in Section 2. The analyzed projects differed in many factors. In Table 3 there are the presented differentiating factors of the 3 example HDD projects. The MAXI HDD projects in the West Pomeranian Voivodeship was the second longest HDD installation in Poland.

In the presented projects, 3 groups of HDD specialists were asked to assess the probability of basic and underdeveloped events occurrence. The experts assessed the probability of the basic and underdeveloped events occurrence based on:

- analysis of the design documentation,
- years of experience during carrying out HDD projects,
- analysis of the failures scenarios described by the author in (Gierczak, 2013),
- analysis of the types of failures in HDD installations described by the author in (Gierczak, 2013),
- analysis of the basic and underdeveloped events and their most important consequences (Table 1),
- analysis of the most important factors determining risk level for all the identified events (Table 2).

Table 4 presents the basic and underdeveloped events with linguistic terms assessing their fuzzy probability of occurrence. Fig. 4 presents the membership function for the probability of the basic or underdeveloped event occurrence, which was constructed for the 3rd group of specialists for the MAXI HDD project in the West Pomerarian Voivodeship. It clearly illustrates the gradual transition from membership to nonmembership. The groups of experts assessing the probabilities of basic and underdeveloped events stressed that they would not be able to give the exact (crisp) values of probabilities. To overcome this problem fuzzy sets were introduced to facilitate gradual transition between states. Their capability to express and cope with the observation and measurement uncertainties was used. Table 5 presents the fuzzy probability of the identified basic and underdeveloped event occurrence for the MAXI HDD project in the West Pomeranian Voivodeship read from the membership function for various values of the membership grade. They were read from Fig. 4 for various α with the step $k = 0.05$.

Fig. 5 presents the distribution of the fuzzy probability of the top event occurrence for the MAXI HDD project in the West Pomerarian Voivodeship (group of specialists no. 3). It was created after calculating the probability of the top event occurrence for various membership grades with the step k from the formula (2). Figs. 6 and 7 present the distributions of the fuzzy probability of the top event occurrence for the MINI HDD project in the Masovian Voivodeship (group of specialists no. 1) and the MIDI HDD project in the Masovian Voivodeship (group of specialists no. 2).

The probability of the top event occurrence of each of the analyzed HDD projects was calculated from the formula (4) and equals respectively $P_t^{COA} = 39.68\%$ for MINI HDD, $P_t^{COA} = 39.98\%$ for MIDI HDD and $P_t^{COA} = 80.76\%$ for MAXI HDD.

For one installation the basic and underdeveloped events probabilities were assessed by two independent group of experts. It allowed to compare the discrepancies in the obtained results.

Table 3
The differentiating factors of the 3 example analyzed HDD projects.

Installation size and province	MINI HDD in the Masovian Voivodeship	MIDI HDD in the Masovian Voivodeship	MAXI HDD in the West Pomeranian Voivodeship
Realization period	09.2008	27.06.2012–28.06.2012	01.07.2012–30.07.2012
The type of installed utility	Pressure sewage system	Pressure sewage system	Casing for 3 cables 15kv
The type of drill rig	Vermeer Navigator D 75 × 100 s/n	Ditch Witch DW 2020 Match 1 JT	Hutte Bohrtechnic GmbH HBR 205D-250
The total length (m)	140	200	1291.23
Maximal depth (m)	8	4	50
Diameter (mm)	355	2 pipes: 200 and 160	355
Pipe material	PE RC	PE RC	Steel
Steering system	Walkover	Walkover	ParaTrack II
Ground conditions	Quicksand, hydrated sands, clay	Sands, sand-gravel mix	Sandy loam, loamy sand with gravel and cobbles, medium sands with gravel, hydrated sand-gravel mix, clay
Planned period of realization (days)	5	2	30
Real period of realization (days)	5	2	45

Table 4
The identified basic and underdeveloped events with linguistic terms assessing their fuzzy probability of occurrence.

Symbol of the event	MINI HDD in in Masovian Voivodeship	MIDI HDD in Masovian Voivodeship	MAXI HDD in West Pomeranian Voivodeship
X1	Very low	Low	Low
X2	Very low	Low	Very low
X3	Very low	Very low	Medium
X4	Very low	Very low	Low
X5	Very low	Low	Low
X6	Very low	Low	Medium
X7	N/A	N/A	Low
X8	N/A	N/A	Medium
X9	N/A	N/A	Very low
X12	Very low	N/A	N/A
X13	Very low	Very low	Very low
X14	Low	Low	Low
X15	Low	Medium	Medium
X16	Low	Very low	Low
X17	Low	Low	Medium
X18	Low	Very low	Low
X19	Very low	Very low	Very low
X20	Very low	Very low	Low
X21	Very low	Very low	Low
X22	N/A	Very low	Low

Table 6 presents the characteristics of the MAXI HDD project in the Lower Silesian Voivodeship.

Table 7 presents the basic and underdeveloped events with linguistic terms assessing their fuzzy probability of occurrence.

Figs. 8 and 9 present the membership functions for the probability of the basic or underdeveloped events occurrence for the MAXI HDD project in the Lower Silesian Voivodeship (groups of specialists nos. 4 and 5). The fuzzy probability of the identified basic and underdeveloped event occurrence for the analyzed project was read from the membership function for various values of the membership grade. The fuzzy probability of the top event occurrence was calculated for various membership grades with the step k from the formula (2).

Table 5
The fuzzy probability of the basic and underdeveloped events occurrence for the MAXI HDD project in the West Pomeranian Voivodeship read from the membership function for various values of the membership grade (for values of α with step 0.05).

Membership grade (α_{jk})	Fuzzy probability of the top event occurrence (%)					
	X2, X9, X13, X19		X1, X4, X5, X7, X14, X16, X18, X20, X21, X22		X3, X6, X8, X15, X17	
	$\widetilde{P_{Xi_{a\alpha_{jk}}}}$	$\widetilde{P_{Xi_{d\alpha_{jk}}}}$	$\widetilde{P_{Xi_{a\alpha_{jk}}}}$	$\widetilde{P_{Xi_{d\alpha_{jk}}}}$	$\widetilde{P_{Xi_{a\alpha_{jk}}}}$	$\widetilde{P_{Xi_{d\alpha_{jk}}}}$
0.00	0.00	5.00	1.00	15.00	10.00	33.00
0.05	0.00	4.80	1.20	14.75	10.25	32.75
0.10	0.00	4.60	1.40	14.50	10.50	32.50
0.15	0.00	4.40	1.60	14.25	10.75	32.25
0.20	0.00	4.20	1.80	14.00	11.00	32.00
0.25	0.00	4.00	2.00	13.75	11.25	31.75
0.30	0.00	3.80	2.20	13.50	11.50	31.50
0.35	0.00	3.60	2.40	13.25	11.75	31.25
0.40	0.00	3.40	2.60	13.00	12.00	31.00
0.45	0.00	3.20	2.80	12.75	12.25	30.75
0.50	0.00	3.00	3.00	12.50	12.50	30.50
0.55	0.00	2.80	3.20	12.25	12.75	30.25
0.60	0.00	2.60	3.40	12.00	13.00	30.00
0.65	0.00	2.40	3.60	11.75	13.25	29.75
0.70	0.00	2.20	3.80	11.50	13.50	29.50
0.75	0.00	2.00	4.00	11.25	13.75	29.25
0.80	0.00	1.80	4.20	11.00	14.00	29.00
0.85	0.00	1.60	4.40	10.75	14.25	28.75
0.90	0.00	1.40	4.60	10.50	14.50	28.50
0.95	0.00	1.20	4.80	10.25	14.75	28.25
1.00	0.00	1.00	5.00	10.00	15.00	28.00

The probability of the top event occurrence of the analyzed HDD projects was calculated from the formula (4) and equals for the 4th group of specialists $P_t^{COA} = 99.71\%$, and for 5th group of specialists $P_t^{COA} = 98.21\%$.

In order to verify the results, the calculated crisp risk level of each analyzed HDD project was compared with the project run. In the case of the MINI HDD project in the Masovian Voivodeship and the MIDI HDD project in the Masovian Voivodeship the projects were completed without any serious problems (it can be also proved by the fact that the planned periods of realization was exactly the same as the real periods of realization (Table 3). In the case of the MAXI HDD project in the West Pomeranian Voivodeship, the real time of realization was longer than the planned due to some problems with drilling fluid seepage (the probability was assessed as medium) and the difficulties connected with drilling in hard clay formations (the probability was assessed as low). In the case of the MAXI HDD project in the Lower Silesian Voivodeship, the project realization took much longer than was planned due to some serious problems, such as unexpected natural subsurface obstacles (the probability was assessed as high by both groups of experts), problems with the external pipe coating (the probability assessed as high by both groups of experts) and a mud cleaning system failure (the probability assessed as medium by both groups of experts). In the four analyzed projects, the risk management strategy was only partly introduced. In future works it will be shown how introducing the actions described in the newly developed risk management strategy for HDD projects influences the risk level of the HDD projects. It was observed that if the final risk level was classified as unacceptable (the borderline for unacceptable risk is calculated assuming medium probability of

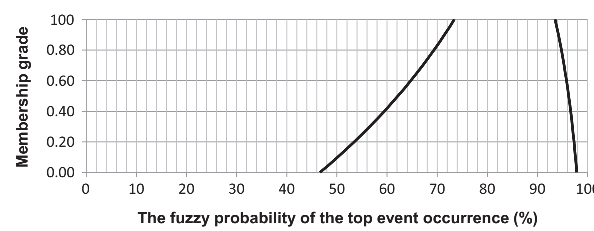

Fig. 5. The distribution of the fuzzy probability of the top event occurrence for the MAXI HDD project in the West Pomerarian Voivodeship.

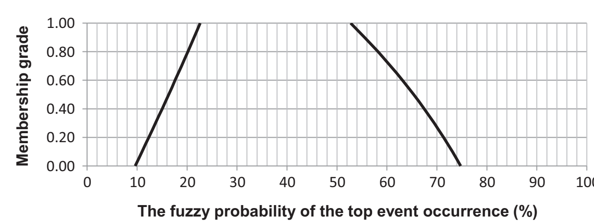

Fig. 6. The distributions of the fuzzy probability of the top event occurrence for the MINI HDD project in the Masovian Voivodeship.

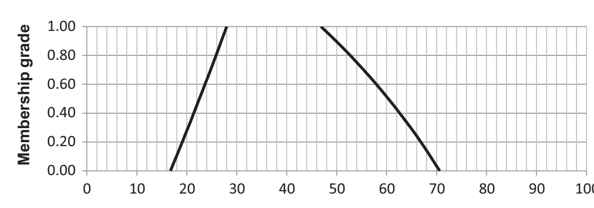

Fig. 7. The distributions of the fuzzy probability of the top event occurrence for the MIDI HDD project in the Masovian Voivodeship.

Table 6
The characteristics of the MAXI HDD project in the Lower Silesian Voivodeship.

Installation size and province	MAXI HDD project in the Lower Silesian Voivodeship
Realization period	09.2008
The type of installed utility	Gas pipe MOP 8.4 MPa
The type of the drill rig	Eletari (pulling force 981 kN , torque 62,000 Nm)
The total length (m)	343.5
Maximal depth (m)	13.8
Diameter (mm)	500
Pipe material	Steel
Steering system	ParaTrack II
Ground conditions	Sandy loam, fine sand, sandy dust, hardpan, sand-gravel mix, cobbles, clay
Planned period of realization (days)	30
Real period of realization (days)	70

Table 7
The identified basic and underdeveloped events with linguistic terms assessing their fuzzy probability of occurrence for two independent groups of experts.

Symbol of the event	4th Group of experts	5th Group of experts
X1	High	High
X2	Very low	Medium
X3	High	High
X4	Medium	Medium
X5	Medium	Low
X6	Medium	Low
X7	Low	Low
X8	Medium	Medium
X9	Medium	Very low
X12	N/A	N/A
X13	N/A	N/A
X14	Medium	Very low
X15	Low	Very low
X16	High	High
X17	Medium	Low
X18	Medium	Low
X19	High	Medium
X20	Medium	Very low
X21	Very low	Very low
X22	Very low	Low

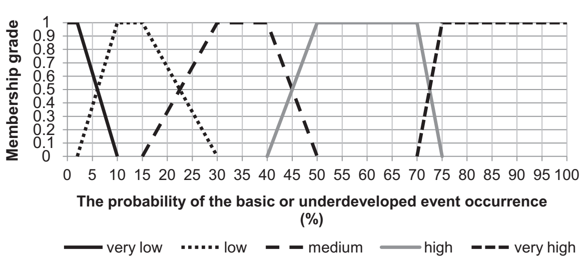

Fig. 8. The membership function for the probability of the basic or underdeveloped events occurrence for the MAXI HDD project in the Lower Silesian Voivodeship (group of specialists no. 4).

one event and very low probability of the rest analyzed events) and the risk management strategy was not introduced, the installation failure occurred. The allowable risk level should be estimated for each analyzed project separately taking into account not only the final risk level of the project but also the value of the Fuzzy Weighted Index calculated during the sensitivity analysis in the risk management step. The risk management step is not discussed in this work due to its ampleness and will be discussed in detail in future works.

The step k between each α is the step with which the extreme values of each event's fuzzy probability are read from the membership function. The step size influences the final results accuracy, e.g. for the MINI HDD project in in the Masovian Voivodeship:

- if $m = 21$, $k = 0.05$, $P_t^{COA} = 39.68\%$,
- if $m = 11$, $k = 0.10$, $P_t^{COA} = 39.57\%$,
- if $m = 6$, $k = 0.20$, $P_t^{COA} = 39.36\%$,
- if $m = 3$, $k = 0.50$, $P_t^{COA} = 38.72\%$.

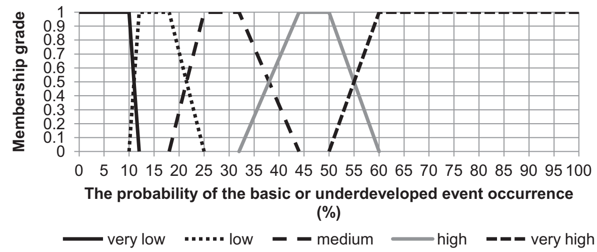

Fig. 9. The membership function for the probability of the basic or underdeveloped events occurrence for the MAXI HDD project in the Lower Silesian Voivodeship (group of specialists no. 5).

During the research, 5 independent groups of expert were assessing the probabilities of basic and underdeveloped event occurrence, so 5 membership functions were created. The membership function with pairs $\langle p, \mu_A(p)\rangle$ for each group of experts is slightly different. It reflects the way in which they understand the term very low, low, medium, high and very high probability. One group of experts could assess the probability of a certain basic event as low, t another one as medium, but if their membership functions are different, it may happen that both expert groups indicated similar fuzzy probabilities (their trapezoidal membership functions for low probability for one expert group and for medium probability for the another expert group would cover each other partially). It is important to mention that the representation depends not only on the concept expressed by the natural language (e.g. low probability) but also on the context in which it is used. In the literature various contexts can be found, e.g. low probability in a context of nuclear explosion or in the context of the weather (e.g. sunny day).

4. Conclusions

The risk level of an HDD project is a key parameter when assessing the project feasibility and making the project pricing. It is also a starting point for introducing a risk management strategy which aims to reduce the number of installation failures and their negative consequences.

The proposed mathematical model of risk assessment in HDD technology enables to carry out qualitative and quantitative risk assessment for the trenchless pipe laying of various sizes (MINI, MIDI and MAXI). It allows to consider the installation specificity (the optional possibility of applying various tools and machines, such as a mud cleaning system, a mud motor, a ballasting system, roller blocks, roller cradles and side cranes). The presented Fault Tree structure clearly shows how various events can interact to lead to an unsuccessful HDD project. It supports the better understating of failure mechanisms.

In the presented mathematical model for qualitative and quantitative risk assessment, the fuzzy sets theory and Fault Tree Analysis were used. Applying the fuzzy set theory in the proposed model allowed to decrease the uncertainty, the lack of precision and difficulties with gaining the crisp values of the basic events probability, which occurs in the conventional FTA.

It was found that 21 unwanted important events affect the risk level for MINI HDD projects: improper calculations of the loads and stresses that exceed the product pipe capacity during the installation, not taking into consideration the allowable bending radius of the drill pipes or the product pipe, the improper choice of the external pipe coating, a loss of communications with the drill rig, drill tool failure due to the material's fatigue, drill rig breakdown, a mud motor breakdown, a mud cleaning system breakdown, roller blocks failure, roller cradles failure, side cranes breakdown, a ballasting system breakdown, downtime in the installation due to unavailable equipment, unexpected natural or man-made subsurface obstacles, a bore hole collapse, a blockage of the drilling pipe or product pipe installation due to the swelling of the clay and silt, drilling fluid seepage, a contractor's error, a problem with the supply and quality, a legal problem, severe weather conditions and one addition for MIDI and MAXI HDD projects – improper cost calculations for the investment.

The presented examples of applications of the proposed risk assessment model prove the possibility of its practical applications. For one MAXI HDD project (a gas pipe installation), the risk assessment was carried out based on the data from two independent groups of experts. The convergence of the obtained results, the top event probability of occurrence $P_t^{COA} = 99.71\%$, $P_t^{COA} = 98.21\%$ confirms the correctness of the proposed model.

References

Abdelgawad, M., et al., 2010. Quantitative assessment of horizontal directional drilling project risk using fuzzy fault tree analysis, vol. 2. In: Conference Proceeding Paper: Construction Research Congress 2010: Innovation for Reshaping Construction Practice, May 8–10, 2010, pp. 1274–1283.

American Society of Civil Engineers, 2005. HDD Design Guideline Task Committee, Pipeline design for installation by horizontal directional drilling, Reston.

Gelinas, M., Mathy, D., 2004. Designing and interpreting geotechnical investigations for horizontal directional drilling, Pipeline Engineering and Construction: What's on the Horizon? pp. 1–10.

Gierczak, M., 2013. Analiza ryzyka w technologii horyzontalnych przewiertów sterowanych, PhD thesis, Kielce University of Technology, Kielce.

Klir, J., Yuan, B., 1995. Fuzzy sets and fuzzy logic. Theory and applications. Prentice Hall PTR, New Jersey.

Kuliczkowski et al., 2010. Technologie bezwykopowe w inżynierii środowiska. Wydawnictwo Seidel-Przywecki, Warszawa.

Ma, B. et al., 2010. Risk evaluation for maxi horizontal directional drilling crossing projects. J. Pipeline Syst. Eng. Pract. 1 (2), 91–97.

NASA, 2002. Fault tree handbook with aerospace applications. NASA Office of Safety and Mission Assurance, NASA Headquarters, Washington.

Naval Facilities Engineering Command, 1986. Soil Mechanics, Design Manual 7, Alexandria Virginia, Fig. 4, pp. 7.1–3.

Shahriar, K. et al., 2007. Geotechnical risk assessment based approach for rock TBM selection in difficult ground conditions. Tunnel. Undergr. Space Technol. 23 (3), 318–325.

Willoughby, D., 2005. Horizontal Directional Drilling – Utility and Pipeline Applications. McGraw-Hill, New York.

Woodroffe, N., Ariaratnam, S., 2008. Cost and risk evaluation for horizontal directional drilling versus open cut in an urban environment. Pract. Period. Struct. Des. Constr. 13 (2), 85–92.

Yager, R., Filev, D., 1994. Podstawy modelowania sterowania rozmytego. Wydawnictwo Naukowo-Techniczne WILEY, Warszawa.

Zadeh, L.A., 1965. Fuzzy sets. Inform. control. 8, 338–353.