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Explosive Charge Applications in Seabed Strengthening for Underwater Pipelines

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ABSTRACT

The importance and impact of subsoil quality is discussed with regard to the safety and reliability of underwater pipelines. Non-classical operational analysis is employed to define generalised dynamic systems. A model incorporating loading of the subsoil acting on a pipeline immersed in an underwater excavation is a specific case of a generalised dynamic system. This paper justifies the incorporation of the analytical method of generalised dynamic systems into the selected model. An innovative, non-standard and effective method is proposed to compact and improve the subsoil for underwater pipeline foundations using blasting charges.

Keywords: transmission system, pipeline transmission, soil improvement, underwater blasting charge.

INTRODUCTION

Due to various needs and functions, the entire transport field may be divided into railways, highways, air transport, and transmission transport classes. The latter are essential and can be sub-divided; however, the term 'transmission pipeline transport' is generally shortened to 'pipeline transport'. Construction and conservation costs are high but the transmission process has low costs and operation times. Low infrastructure flexibility is one disadvantage of such a transport type because only a single substance may need to be transmitted. Petroleum and gas are the most popular feedstocks being pipeline-transmitted (through pipelines and gas pipelines) and pipeline transport is safer than the alternatives, e.g. tanker transport.

The increasing need for energy feedstock is a development vehicle of this transport branch. The design process of a pipeline begins with route mapping in variable soil and terrain conditions, including underwater cases. The latter include underwater pipelines (subsea pipelines). Route planning is affected by the route length, the preliminary work required in each region, and the physical and mechanical parameters of the soils which will support the line. Underwater pipelines make it necessary to investigate the seabed prior to pipe laying.

Pipeline design needs to consider its resistance to external pressures, internal loadings, anchoring facilities, the medium weight during hydrostatic tests, methods of fixing the manifolds and supporting elements, hydrostatic buoyancy, atmospheric phenomena, soil settlement, soil volume expansion (due to heavy frosts), soil creep, seismic and para-seismic shocks, and temperature impact. When all of these criteria are satisfied, safe pipeline operation is assured.

In most cases, the subsea pipelines are long-distance routes, reaching lengths of several hundred kilometres. Various laying routines can be applied, e.g. the S-method or the J-method. The method is chosen based on the features of the specific seabed, its depth and working distance from the coast. Examples of offshore oil and gas pipeline systems are transportation systems in the North Sea, the Gulf of Mexico, and the Baltic Sea [2].

The Baltic Sea is a demanding water reservoir because it is relatively shallow, shows low salination and has limited water circulation, which is retarded by the Danish straits. Pipeline projects have to examine their environmental impact, in order to minimise the negative consequences of the pipeline for the Baltic Sea eco-system. The construction and continuing operation of the pipeline detected no negative impact on the nature of the Baltic Sea; the ecosystem is subjected to constant monitoring.

The next example of an underwater pipeline is a planned (conducted) Baltic gas pipeline with a 10 billion m^3 capacity, connecting the Polish and Danish transmission systems, making it possible to explore the Norwegian gas deposits. This project contributes to the North-South Corridor concept and the Baltic Energy Market Interconnection Plan (BEMIP). Both of these are priorities in the development of power engineering infrastructure under the EU's auspices.

A pipeline structure needs to ensure its appropriate protection; sometimes it is necessary to trench the pipeline or to cover it by rock material (Baltic Pipe: Polish Information on the proposed activity Espoo Convention – Art.3). Trenching is conducted using a drilled ditch, with the operation being conducted by a trailing suction hopper dredger at depths below 6 m. At depths above 6 m, special pipeline ploughs are used (Fig. 1).

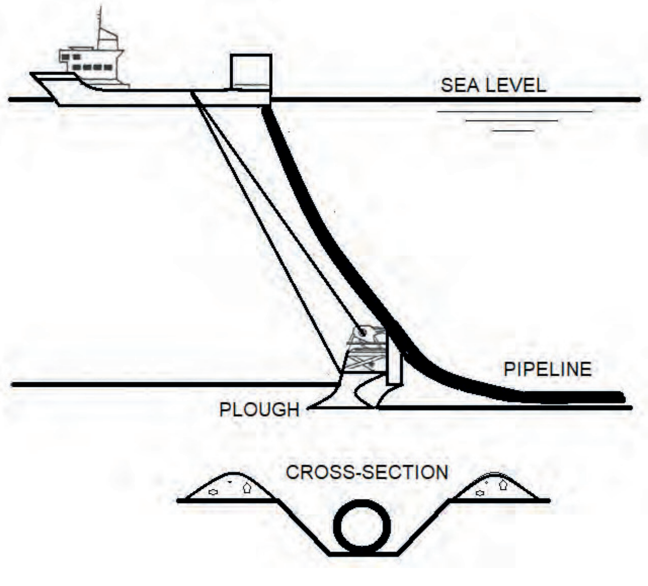

Fig. 1 Trenching the pipeline by plough

In this case, the pipes are laid on the sea bed and then excavation is carried out using a special plough, see Fig. 1. The next pipe protection variant of the pipeline is structural strengthening (pipeline protection) by introducing a rocky material. Fig. 2 presents the process, using vessels equipped with a Dynamic Positioning System (DPS) and a flexible downpipe, as shown in Fig. 2. The pipe is dropped down to the water just under the ship.

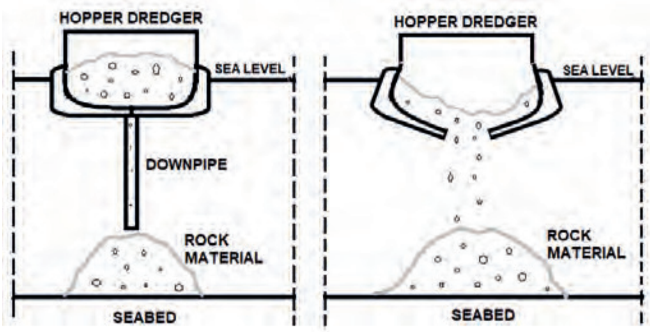

Fig. 2. Stacking variants of a rocky material

Previous studies pointed out the key role of the subsoil and its improvement or strengthening could be decisive for the safety, reliability and durability of the pipeline.

THE IMPACT OF SUBSOIL QUALITY ON PIPELINE SAFETY AND RELIABILITY

The issue of technical safety in transmission gas pipelines is complex. Technical safety is achieved by dedicated operations, including those rejecting the impact of pipeline settlement. Pipeline settlement may lead to 'unsealing'. These operations are intended to minimise failure probability, which can also be triggered by hydraulic impact, elevated stresses, and strains in the pipeline shell.

In technical terms, the pipeline is safe when its technical conditions ensure its reliability and durability. To ensure a relevant pipeline safety level, permanent observations are required, including settlement measurements. These observations are employed to assess the current technical state of the pipeline. They may also be incorporated to estimate the longevity of a proper pipeline operation, i.e. safe and reliable transmission of a given medium (e.g. gas or petroleum) for a given working pressure. Estimation of corresponding probabilities needs to consider the current information on the length of a transmission network and its settlement on the subsoil.

Possible pipeline damage, and its results, acts negatively on the reliability of a pipeline as a means of transmission transport. It impacts the reliability of an entire pipeline system or its elements and it is assumed that the entire pipeline and all its elements work properly until failure. The time of proper work of the pipeline analysed is a random variable T of a specified probability distribution affected by the object/pipeline features, operating conditions (regarding pipeline settlement controlled by the subsoil, its conditions, and compaction), and a number of features marking its safe working ability. Every random variable is defined by its cumulative distribution function (CDF).

$$F(t) = P(T \leq t) \quad (1)$$

In our case, the probability of the proper work time, i.e. the failure function, leads to the reliability function *R(t)*,

$$R(t) = 1 - F(t) \quad (2)$$

Reliability in the pipeline safety modelling makes it possible to employ the damage function $\lambda(t)$, defined by

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{P(t < T \leq t + \Delta t | T > t)}{\Delta t} \quad (3)$$

making use of the conditional probability of pipeline damage in the time interval (t, $t + \Delta t$), given its proper work until the time instant t. It is essential that the damage intensity function is linked to the *R(t)* function by

$$\lambda(t) = -\frac{d}{dt} lnR(t) \quad (4)$$

and

$$R(t) = e^{-\int_0^t \lambda(\tau)d\tau} \quad (5)$$

while the initial time instant yields $R = 1$.

Practical applications make it possible to introduce various random variable distributions of T. The adjustment is made to a relevantly large observation domain (e.g. pipeline settlements) and the popular types are: exponential, bounded (truncated) Gaussian, Weibull, and others. Given the distribution type, $R(t)$ and $\lambda(t)$ may be determined to forecast the renovations or repairs required to optimise the erection time (Fig. 3).

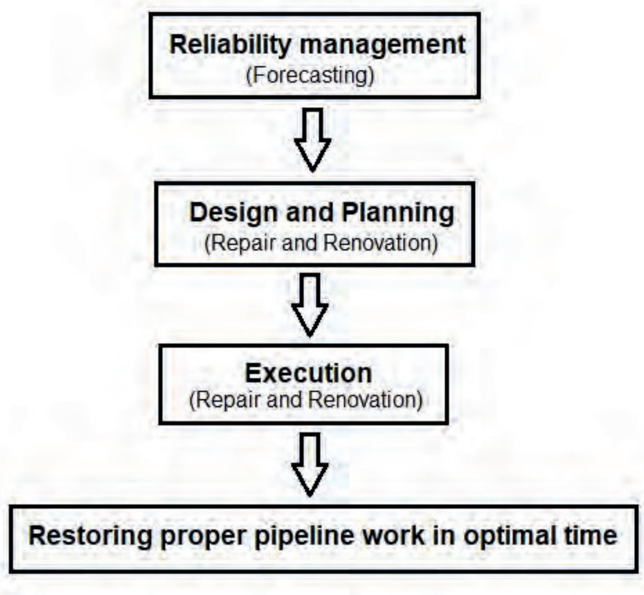

Fig. 3. Restoring proper pipeline work

GENERALISED DYNAMIC SYSTEMS IN THE SUBSOIL LOADING ANALYSIS FOR UNDERWATER PIPELINES

While the pipeline is being trenched into the seabed (Fig. 1) (rather than just lying on it), additional excavation loads act upon it, see Fig. 4.

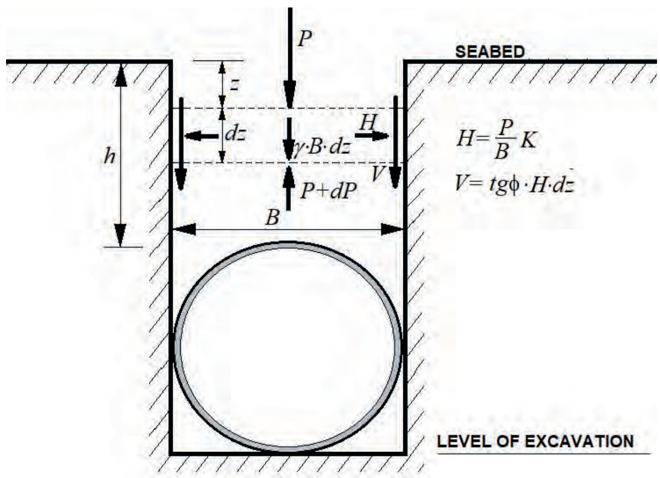

Fig. 4. Illustration of Eq. (1)

While rocky material is being laid (Fig. 2), its mass represents an extra load. As the pipeline is immersed in the soil of the seabed, the subsoil under the pipeline becomes loaded by the backfill; Fig. 4 shows the weight of the pipeline and the flowing medium. Hydrostatic pressure is also considered. The image in Fig. 4 makes it possible to formulate the differential equation (similar to the case in [2]), due to soil load P acting on a pipeline laid in a shallow excavation.

$$\frac{dP}{dz} - \alpha(z)P = f(z) \quad (6)$$

$$\alpha(z) = \frac{2K}{B} tg\Phi \quad (7)$$

$$f(z) = \gamma B \quad (8)$$

The symbols used in Fig. 4 and Eq. (6) are defined as:
γ – unit weight of the backfill
B – pipeline (excavation) diameter
$K = 1 - sin\Phi$ or $K = tg^2(45 - \frac{\Phi}{2})$– coefficient of earth pressure
h – soil depth above the pipeline
Φ – angle of internal friction
T – friction on the sides
z – according to Fig. 4

The coefficient $\frac{2K}{B} tg\Phi$ is affected by z, while the internal friction coefficient is not constant for a given soil. It is controlled by a number of factors: the stress state within the soil, the shearing rate of the soil, and drainage conditions in the soil.

Eq. (6) leads to the P value and non-classical operator methods, incorporating non-classical operator analysis, are effective here. This method allows us to determine generalised dynamic systems, which can be used to analyse the subsoil loading of underwater pipelines, and this is important in our case.

The non-classical operator analysis is based on three linear operations:

$S, s_q, T_q, q \in Q$, which represents the index set in two linear spaces: L^1 and $L^1 \subset L^0$, $S: L^1 \to L^0$, $T_q: L^0 \to L^1$, $s_q: L^1 \to KerS = \{c \in L^1: Sc = 0\}$ and $ST_q = id$, $T_qS = id - s_q$.

The operations $S, s_q, T_q, q \in Q$ and their various features may be found in [10,11].

It is important that these operations are defined in both discrete and continuous domains, leading to differential equations or systems which can define, explain and analyse generalised dynamic systems [11].

If we assume that the spaces L^1 and L^0 are algebras with a unit **1** and multiplication, then:

$$S(fg) = (Sf)g + f(Sg), f, g \in L^1$$

and s_q is a multiplicative operation. The assumptions resembling those in [11] make it possible to apply the operator methods to analyse generalised dynamic systems of the form:

$$a_1 Sx + a_0 x = u \tag{9}$$

Here: $a_0, a_1 \in L^0$, $u \in L^0$, $x \in L^1$.
Remarks: If a_0, $a_1 \in R$, then additional assumption L^1, L^0 is unnecessary.

A specific form of the latter generalised dynamic system is a generalised inertial term of the first order [11]. With regard to the assumed representation of operator analysis in (9), the systems of point and distributed parameters arrive at the result [11]. The operation S is decisive here.

The response of a generalised dynamic system (9) reads with the help of the following theorem [11].

If a_1 is a reversible element and there is an element $E_{\mathbf{1}}^{T_q(a_1^{-1}a_0)}$ the response of a dynamic system (9) with a condition $s_q x = x_{0,q}$, $x_{0,q} \in KerS$ is a one-to-one solution, expressed by:

$$x = \left[T_q\left(a_1^{-1} u E_{\mathbf{1}}^{T_q(a_1^{-1}a_0)}\right)\right] E_{\mathbf{1}}^{-T_q(a_1^{-1}a_0)} + x_{0,q} E_{\mathbf{1}}^{-T_q(a_1^{-1}a_0)} \tag{10}$$

In this theorem, the element $y = E_{\mathbf{1}}^{T_q p}$ is a reversible solution of the equation $Sy = py$, $y \in L^1$, $p \in L^0$ with a condition $s_q y = \mathbf{1}$. When this element exists it is unique.

The operator analysis model has the operations:

$$S = \frac{d}{dt}, \; T_q = \int_0^z, \; s_q = |_{z=0} \tag{11}$$

which makes it possible to apply (3) to determine a structural response (1), upon the condition $P(0) = P_{0,0}$.

In general, if $\alpha(z)$ and $f(z)$ are affected by (z), the P value reads:

$$P = \left\{\int_0^z f(\tau)\exp\left(\int_0^\tau(-\alpha(\xi)d\xi)d\tau\right)\right\}\left\{\exp\left(-\int_0^z(-\alpha(\tau))d\tau\right)\right\} + \\ + \left\{P_{0,0}\exp\left(-\int_o^z\left(-\alpha(\tau)\right)d\tau\right)\right\} \tag{12}$$

Upon transformation, the last equation reads:

$$P = \left\{\int_0^z f(\tau)\exp\left(\int_0^\tau(-\alpha(\xi)d\xi)d\tau\right)\right\}\left\{\exp\left(-\int_0^z(-\alpha(\tau))d\tau\right)\right\} + \\ + \left\{P_{0,0}\exp\left(-\int_o^z\left(-\alpha(\tau)\right)d\tau\right)\right\} \tag{13}$$

It should be noted that, if $\propto(z) = \propto = const$, then:

$$P = \left\{\int_0^z f(\tau)\exp(-\alpha\tau)\,d\tau\right\}\exp(\alpha z) + P_{0,0}\exp(\propto z) \tag{14}$$

Additionally, if $f(z) = f = const$, then:

$$P = \left\{f\int_0^z \exp(-\propto \tau)\,d\tau\right\}\exp(\alpha z) + P_{0,0}\exp(\propto z) \tag{15}$$

The last equation yields:

$$P = -\frac{f}{\propto}[\exp(-\propto z) - 1]\exp(\propto z) + P_{0,0}\exp(\propto z) \tag{16}$$

$$P = \frac{f}{\propto}[\exp(\propto z) - 1] + P_{0,0}\exp(\propto z) \tag{17}$$

While only $f(z) = f = const$; however, $\propto(z)$ is affected by z, hence:

$$P = f\left\{\int_0^z \exp\left(-\int_0^\tau \alpha(\xi)d\xi\right)d\tau\right\}\exp\left(\int_0^z \alpha(\tau)d\tau\right) + \\ + P_{0,0}\exp\left(\int_o^z \alpha(\tau)d\tau\right) \tag{18}$$

Each equation may serve for determining the P value of a load acting on a pipeline at $z = h$ (see Fig. 4). In the most general case (i.e. where $\alpha(z)$ and $f(z)$ are controlled by z), the pipeline load P at $z = h$ is determined by:

$$P = \left\{\int_0^h f(\tau)\exp\left(\int_0^\tau(-\alpha(\xi)d\xi)d\tau\right)\right\}\left\{\exp\left(-\int_0^h(-\alpha(\tau))d\tau\right)\right\} + \\ \left\{P_{0,0}\exp\left(-\int_o^h\left(-\alpha(\tau)\right)d\tau\right)\right\} \tag{19}$$

Therefore, in the analysed case, the thrust on the subsoil under the pipeline is affected by a multitude of factors, so it should be regarded in subsoil improvement or strengthening. The additional impact of hydrostatic pressure, the weight of the pipeline and the flowing medium, the flow character [1], and hydraulic shocks make it necessary to improve or strengthen the subsoil in the light of its safety. An innovative technique to apply the blasting charge seems advantageous here.

FUZZY LOGIC AS A TOOL FOR ANALYSING PIPELINE SERVICIBILITY

In engineering practice, monitoring all of the parameters that influence pipeline behaviour is unrealistic. It is also difficult to establish correlations between those parameters. The evaluation of structural safety requires the identification of loading, the characteristics of the materials used, and the soil parameters [9] taken as input data in geotechnical design. Structural reliability also means comparing the existing state with the desired state of the structure. The evaluation may be required to assist soil improvement, pipeline components, or the overall structure. The actual condition may be estimated as being *low*, *medium*, or *excellent*. These are also 'fuzzy' concepts. At this stage design, expert methods and the fuzzy set theory plays a significant role.

In fuzzy set theory, for sets X and U [8,12], the membership function $\mu_X(x)$ is defined as follows:

$$\mu_X(x) = \begin{cases} f(x) \in <0,1> & for\ x \in X \\ 0 & for\ x \notin X \end{cases} \quad , x \in X \subset U \qquad (20)$$

because an element may 'partially' belong to a given set. For example, the function of membership of a fuzzy set can be usefully presented as broken line graphs [12].

After the partitioning of the pipeline into sections, membership functions may be assigned to each of them. The functions concern issues such as the soil settlement under the pipeline, the risk of pipeline deformation, and the risk of pipeline leaking.

Assuming various criteria, which are dependent on several factors, the analysis of pipeline behaviour may be established. It may be helpful to order the factors into a hierarchy of importance. In this process, evaluation is executed according to the AHP method (Analytic Hierarchy Process). The rating scale of evaluation is taken as being from 1 to 9 [12]. For matrix evaluations, elements, eigenvalues and eigenvectors are determined. The weights created by these eigenvalues and eigenvectors indicate the hierarchy of importance of the factors in the criteria considered.

Using the AHP method allows different topics to be analysed: connection and integrity of the structure; materials; maintenance strategies; environmental influences (low, medium, high); ecological effects; subsoil settlement reduction; and design features (the arrangement and power of charges). These must be supported by observations and expert know-how.

COMPACTION (IMPROVEMENT) OF UNDERWATER SUBSOILS BY THE BLASTING CHARGE METHOD

Dynamic compaction of the subsoil by blasting charge operations is a useful technology for strengthening both non-cohesive and cohesive, fully water-saturated soils [7]. The physical phenomena accompanying the detonation of an explosive located in the subsoil (or on its surface) result in an immense shockwave and a rapid water pressure rise in the pores of the soil [3]. In non-cohesive soils, this leads to temporary liquefaction around the explosion zone; water pressure dissipation causes the soil particles to become compacted [5]. In cohesive and organic soils, the method is incorporated in an overall soil replacement method to accelerate the consolidation in the shockwave part beyond the soil replacement zone.

At the moment of the explosion, the accumulated energy dissipates in an extremely short time. It triggers a rapid action in the subsoil in the vicinity of the explosion. This impulse overloads the soil, producing excessive soil deformation [6]. Therefore, the explosives located on the soil surface create localised caverns of well compacted soil, ready for the direct construction of foundations (Fig. 6). Further away from the blast, the shockwave transforms into a para-seismic wave, which affects the soil structure, triggering advantageous compaction and a reduction in soil porosity. The application of vertical longitudinal explosives is justified in soil strengthening cases at greater depths [13].

The soil strengthening method utilising blasting charges has been widely applied in Polish hydro and marine civil engineering, particularly at the nuclear power plant construction site in Żarnowiec and the box foundation for the Northern Harbour in Gdańsk [4].

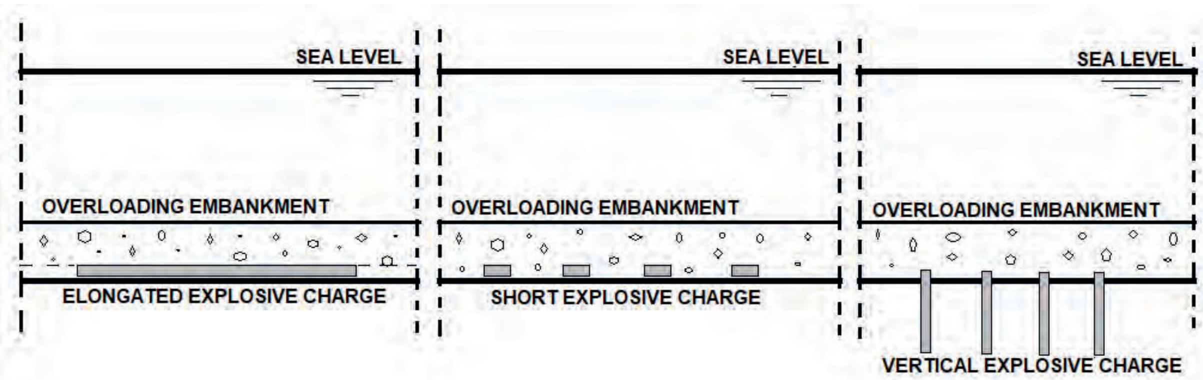

Fig. 5. The installation variants of explosives under a loading backfill, the overview along the pipeline route

The foundations of transmission pipelines require specific geotechnical precision when preparing the subsoil. The pipelines are long-distance transmission structures and soil conditions may vary with distance; geotechnical work may also be demanding. The subsoil of the seabed may be diverse, from liquid-like organic soil layers to soft sedimentary rocks (of silty origins) and highly sensitive to dynamic loads.

The loading of a pipeline's subsoil is a dead and variable weight; it is transmitted to the medium and impacts dynamic pressure shocks on the pipeline. Such dynamic loads may cause excessive vertical and horizontal deformations of the pipeline.

in parameters, including the soil characteristics. The disadvantageous dynamic impact of a pipeline on the subsoil (e.g. triggered by hydraulic shocks) may be limited by an innovative strengthening method of subsoils for underwater pipelines. This underwater blasting charge method is proved to be successful and effective.

It is crucial to note that analytical models and risk evaluation should be created based on knowledge, experience and intuition. Some levels of accuracy (probabilistic) may be neglected but that approach links the knowledge obtained from observations, experience and expert skills.

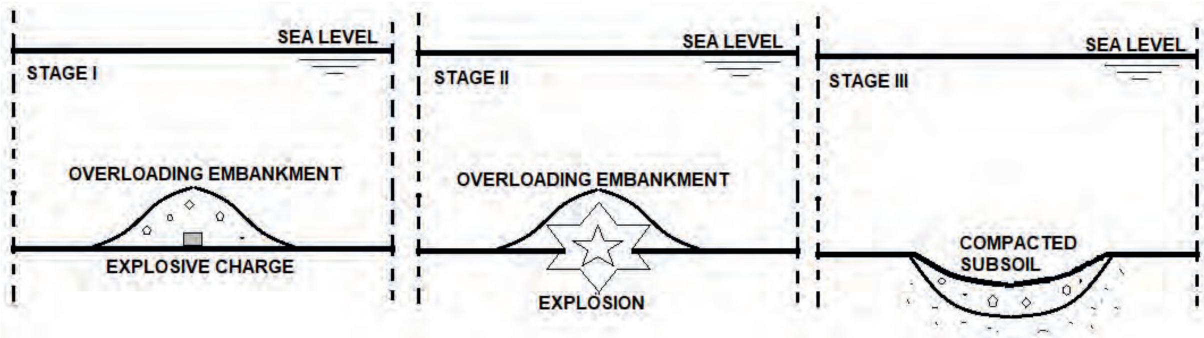

Fig. 6. The stages of subsoil improvement, an overview in the cross-section of the pipeline route:
Stage I – installation of the explosive and the loading backfill
Stage II – ignition of the blast
Stage III – subsoil preparation for pipeline laying

Well-prepared subsoil should compensate for the normal and shear loads applied to it, not allowing for excessive structural deformations. The compaction method utilising blasting charges on the subsoil for underwater pipelines, including an overloading backfill (Fig. 5), is less complicated than other technologies. Experience shows us that the method meets expectations and is successful.

CONCLUSIONS

Non-uniform soil settlement under a pipeline may lead to its 'unsealing'. In extreme cases, such an event may cause tearing of the pressure vessel shell on one side and shell deformation on the other side. Appropriate preparation of the subsoil (by improving it) minimises non-uniform pipeline settlement, increasing its load-carrying abilities, reliability and durability. In the analysis of underwater pipelines, the non-classical operator solution methods have proved to be successful.

The differential equation of the *P* force problem, produced by the soil acting on the pipeline immersed in the soil, is an example of a generalised dynamic problem.

The methods for determining dynamic system responses may be successfully incorporated, to determine the load *P* at variable soil conditions. The operator methods make it possible to investigate the system's sensitivity to changes

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