Automatic device elaboration for grouting bag setting under free spanning of submarine pipelines

B Zhang¹, Z Wang¹,² and T Wang²

¹College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001 China
²School of Mechanical Engineering, Hebei University of Technology, Tianjin, 300401 China

*E-mail: wangzhuo_heu@hrbeu.edu.cn

Abstract. A new grouting support method is proposed to solve the problem of divers. Those dispose of the free spanning submarine pipelines by the traditional grouting support method, which may have low efficiency and security. The equipment, which is designed to replace the divers to operate by setting grouting bags under the spanning pipes automatically, reduces the difficulty of the divers’ operation and the working time in the water, and makes the working process more automatized. Based on the wave theory, the wave load on the grouting support and the frictional force of the seabed on the support are analyzed. The deformation of the grout bag is calculated by the finite element method, to ensure that the stiffness is sufficient to meet the strength requirements. After the mechanical and electrical system design of the equipment and the simulation experiment, it was proved that the equipment operation under work conditions is reliable, and the proposed modification is effective.

1. Introduction
Free span of pipelines can cause vortex-induced vibration of pipes, which may lead to their fracture [1]. This is one of the main factors threatening the safety of submarine pipelines. At present, methods of disposing of spanning pipes can be subdivided into four categories: landfill treatment, support management, blocking flow and smooth siltation technology, along with a pipe. For the sake of technology, the engineers used the falling stone method to support the spanning pipes [2] in the Ormen Lange project in Norway. The treatment used in this project and this innovative type method was introduced in [3-4].

The technology consists of many specific methods, such as sandbag support method, steel column support method, grouting bags support method, etc. The sandbag support method was utilized to deal with the spanning pipes in the oilfield of the Gulf of Mexico and the North Sea [5]. In the Canyon Express oilfield project in the Gulf of Mexico and the Ceiba Field project in West Africa, a steel column support method was used to manage the pipe-suspension [6]. Grouting support method is to set grouting bags under the spanning part of the pipe and then inject grout into the grouting bag through grouting equipment on the working ship. After the solidification of cement in the grouting bag, the bag will provide reliable support to the pipe [7].

In the United States, Britain, Mexico, and other countries, engineers have used the bionic water plants method in the pipe spanning project [8]. The engineers have used steel structure support method along with bionic water plants method to dispose of the spanning of pipes in the platform numbered CB35 in...
Cheng island oilfield [9]. Guide plate method has been used in Green Canyon Block oilfield in the Gulf of Mexico and North Sea [10]. The floating curtain blocking method was invented by Shanghai Jiao Tong University, which has been proved to be feasible to manage the spanning pipes [11].

After a comparison of each method, support management technology is advantageous for being easy to implement and provide stability. The grouting support method has better adaptability to the seabed, and it can offer more extended support to the pipe. As a result, the method has the shortcoming of low operating efficiency and high risk to divers. The research is on to improve the traditional grouting method. The focal point of the new type of grouting method is to design equipment which can fulfill the task of setting grouting bags automatically.

The suspending grouting bag treatment device is designed for the submarine pipeline in this paper which is different from other equipment. In this method, 5-6 grouting bags are in water every time and processing 5-6 suspending points in turn. Moreover, the specially designed laying grouting bag mechanism can realize the automatic laying of the grouting bag underwater.

In this paper, the load of the grouting support in the working condition is calculated through the wave theory to analyze its stability. The deformation of the grouting bag is analyzed by the finite element method to check its safety. After the analysis of the theory, the authors have prepared the design of the equipment and built a prototype machine to do the experiment.

2. Brief introduction and feasibility for the analysis of the new type of grouting method

2.1. Introduction of the scheme
The purpose of this paper is to modify the traditional grouting support method. According to the statistics from the investigation of projects about spanning pipes, these are finished before the general height of the suspension, 0.6~2.0 m, and the maximum depth of water about 60 m. The equipment is the critical point of this work, and it needs to be reliable in the working conditions.

Considering the situation that the grouting support may sink with the seabed movement, so the engineers need to inject the cement into the grouting bag for the second time. To increase the contact area of the pipe and the support, the A-shaped structure is selected to the outline of the bag. And the sandwich layer at the bottom of the bag is designed for the second injection.

2.2. Reliability analysis of grouting support
The impact of seawater on the grouting support is composed of wave and current load. The wave load produces a periodic horizontal impact on the grouting support. The current load produces a constant effect on grouting support.

Based on the shape of the grouting bag, the load of the bag can be calculated by the Morison equation. To facilitate the analysis, the following coordinate system was established, as is shown in figure 1.

Figure 1. Schematic diagram of the impact of the wave to the support.
The horizontal wave force of single grouting support structure is calculated by the microelement method. It can be calculated via Eq. (1).

$$F = \int_0^l \frac{1}{2} C_D \rho u_s |u_s| \left[ b + \frac{(a-b)}{l} z \right] dz + \int_0^l C_M \rho \left[ b + \frac{(a-b)}{l} z \right] \frac{\partial u_s}{\partial t} dz$$

(1)

where $F$ is the horizontal force generated by the waves working on the grouting support; $l$ is the height of the whole grouting support; $C_D$ is the coefficient of the drag force generated by the waves; $\rho$ is the density of seawater; $u_s$ is the horizontal velocity of the particle of the wave at the position of microelement without the grouting support; $a$ is the side length of the upper surface of the grouting support; $b$ is the side length of the lower surface of the grouting support; $z$ is the distance between the microelement and the surface of the seabed; $dz$ is the height of the microelement; $C_M$ is the coefficient of the inertial force; $\frac{\partial u_s}{\partial t}$ is the horizontal acceleration of the particle of the wave at the position of microelement without the grouting support.

Given the working conditions, the horizontal velocity and acceleration of the waves can be calculated by the Airy wave theory [12].

$$\begin{align*}
    u_x &= \frac{\pi H \cosh kz \cos(\theta)}{T \sinh kh} \\
    a_x &= \frac{2\pi^2 H \cosh kz}{T^2 \sinh kh} \sin(\theta) \\
    \theta &= kx - \omega t
\end{align*}$$

(2)

where $H$ is the height of the waves; $T$ is the cycle time of the waves; $h$ is the depth of seawater; $\theta$ is the phase angle of the waves; $k$ is the number of the waves in certain time; $x$ is the horizontal coordinate; $\omega$ is the angular frequency of the waves; $t$ is the time of the motion of waves. Based on Eq. (2), the effect of each factor on the horizontal velocity and acceleration of waves is depicted in figure 2.

![Figure 2](image)

**Figure 2.** Effect of phase angle and depth of water on the horizontal velocity and acceleration of the waves.

As shown in figure 2(a) and (b), the effect of phase angle and the depth of water on the horizontal velocity and acceleration of waves are increasing gradually with the increasing distance between the seabed and microelement. At the position of sea level, the speed and acceleration have the maximum value. In other words, with the increasing depth of water, the value of velocity and acceleration decreases
gradually. When the depth of water reaches a certain value, the speed and acceleration have been close to zero, and then their impact can be neglected. From the analysis, the horizontal velocity and acceleration of waves are affected by many factors. In engineering projects, the depth of the working area is often known from pre-observation and engineers choose the maximum velocity and acceleration of the motion of waves to do designing calculation [13]. It is generally considered that the depth of water exceeds the length of waves by 0.5 times, the area can be regarded as a deep water area. Taking \( u \) and \( a \) into the Morison equation, the horizontal force generated by the waves working on the grouting support can be calculated by Eq. (3).

\[
F = K_D A_D \cos \theta \cos \theta + K_M A_M \sin \theta
\]  
(3)

In Eq. (3), the coefficient can be calculated by the following equations from the combination of the Morison equation and the Airy wave theory.

\[
\begin{align*}
K_D &= \frac{(b-a)}{4} + \frac{a \sinh 2kl}{4k} + \frac{(b-a) \sinh^2 kl}{4k' l} \\
A_D &= \frac{\pi^2 C_a \rho H^2}{2T^2 \sinh^2 kh} \\
A_M &= \frac{2\pi C_a \rho H}{T^2 \sinh kh} \\
K_M &= \frac{a \sin kl}{k} + \frac{(a-b)(1-\cosh kl)}{k' l}
\end{align*}
\]  
(4)

Next, we calculate the derivation of time in the Eq. (3) and assume a zero value of the derivative, to find out the maximum horizontal load of the grouting support from the waves. The extreme value of wave load is affected by the depth of water, action time, and cycle time, the height of the wave and the height of grouting support. Considering the trend of each factor, the extreme value of wave load can be expressed as:

\[
F_{\text{max}} = K_M A_M
\]  
(5)

Choose the hydrodynamic parameters and take the parameters of the structural size of the grouting bag and the working conditions into Eq. (4) and Eq. (5), \( C_u = 2.5, C_a = 2 \), to find out the maximum value of \( F \).

After finding out the load of the wave on the grouting support, it is necessary to find out the effect of the current load on the grouting support. The current load on the grouting support can be calculated still by the Morison equation.

\[
F = \int_{-z}^{z} \frac{1}{2} C_o \rho u^2 \left[ b + \frac{(a-b)}{l}z^2 \right] dz = \frac{C_o \rho u^2 (a+b)l}{4}
\]  
(6)

where \( A \) is the area of the surface perpendicular to the direction of ocean current; \( u \) is the horizontal velocity of the particle of the seawater. Based on Eq. (6), the load of the ocean current can be calculated, \( C_o = 2, u = 0.6 \text{ m/s.} \) considering the calculation of the wave load, the relationship between the wave-current combined load and the height of grouting support is shown in figure 3.

As seen in figure 3, the wave-current load on the grouting support tends to be a constant with the increasing depth of water. To ensure the reliability of the support, the value of wave load and current load increases to the maximum appropriately in the calculation.
Assume that $G_p$ is the gravity of the pipe; $F_p$ is the force on the grouting support from the pipe; $F_f$ is the friction on the support from the seabed; $F$ is the wave-current on the support; $F_1$ is the component force in the direction along the inclined surface of the support. $F_2$ is the component force in the direction perpendicular to the inclined surface of the support; $G_s$ is the gravity of the grouting support.

Then, $G_p$ and $F_p$ can be calculated by the microelement method as follows:

$$
G_p = \int_0^1 \int_0^\pi \rho \frac{ad}{2} \cos \theta d\theta d\phi
$$

$$
F_p = \int_0^1 \int_0^\pi \rho \frac{ad}{2} \sin \theta d\theta d\phi
$$

(7)

where $d$ is the diameter of the pipe. The maximum length of the spanning part of pipe is 10 m based on the investigation. The frictional force on the bottom of the grouting support from the seabed can be calculated via Eq. (8).

$$
F_f = \mu(G_p + G_s)
$$

(8)

where $\mu$ is the coefficient of friction of the sea bed.

The density of cement is 1.5 g/cm$^3$ and the coefficient of friction of the seabed is 0.1. The frictional force is calculated from Eq. (8). The surface of the seabed is rougher than the ideal situation, so the actual friction is larger than the calculation.

From the calculation, the frictional force on the grouting support is much larger than the horizontal combined load of wave-current. Therefore, the support will not slip on the seabed. The design pressure of the grouting bag is 0.8 MPa and is designed for working water depths of 60m. The grouting bag needs to be tough enough to bear the load of waves. The deformation of grouting bags without cement inside can be analyzed by the finite element method. The modulus of elasticity, the tensile strength, Poisson’s ratio and density of the bag material (namely, composite nylon) are 6.2 GPa, 3.76 MPa, 0.35 and 1.15, respectively. The upper surface and the lower surface of the bag are fixed. The result of the simulation is shown in figure 4. It can be seen in figure 4 that the maximum deformation of the grouting bag is 163 mm and it is located in the middle of the side surface. The maximum strain is within the allowable range, and the grouting bag meets the engineering requirements.
3. The mechanical system design of the equipment

3.1. The structure and components of the device

The main aim of this study is the elaboration of three-dimensional design for the automatic bag-setting device. The latter consists of the frame, mechanism of propulsion, support; locking, and balance, controller, as well as other components. The container of the grouting bag is a drawer-shaped slider, which facilitates bag-setting and keeps their stability. The device can carry six sliders so that it can deal with six working positions in one process. The mechanism of propulsion is utilized to push the lowest slider out of the frame to the working position under the spanning part of the pipe. The whole structure is shown in figure 5.

The mechanism of balance
The container of grouting bags
The mechanism of support and locking
The mechanism of propulsion

3.2. The working process of the device

The fabricated equipment is sent to the working position by the lifting equipment on the moving ship and the help of ROV (remote operated vehicle) and divers. In the beginning, the mechanism of support and locking was working, and the support part of the mechanism was holding up the sliders except the one at the bottom of the device. Then, the mechanism of propulsion was to push out the bottom slider and to set in the working position. After that, the mechanism of support and locking was working to let the rest of sliders fall down. The next slider was pushing out to be in position. Engineers on the working ship are supposed to inject cement to the grouting bag through the pump and pipelines. The grouting bag is expanding while the bag is filled with cement. When the support is formed, the diver will cut off the pipeline of transporting cement and the device will be taken to another working place. When the

Figure 4. Total deformation of the outer surface of grouting bag.

Figure 5. The structure of the automatic bag-setting device.
sliders are running out, the process is over, and the engineers will bring back the device. The whole work process can be expressed by the figure 6, where (a) shows that the device reaches the working position, (b) the device is setting grouting bag, (c) The final effect of the treatment.

Figure 6. The working process of the device.

4. The prototype device test

To verify the motion of the device, a prototype was fabricated for the study. The experiment is intended to simulate the work condition of the device in the seawater to check its reliability. There are five steps in the experiment.

(1) The height of the pipeline was adjusted by the adjusting screw of the test application. It was used to simulate different heights of spanning pipes. The pipe is needed to be horizontal during the experiment.

(2) Each slider was set into the device through the crane, and the grouting bags were placed into the sliders.

(3) With the help of the controller to control the device for finishing the expected motion. All the mechanism work was undertaken in turn to push out the slider to the spanning position. The time of each motion of the device was recorded.

(4) The level of strength of the cement was 52.5, and the proportion of the slurry of the cement was 1.9. This kind of slurry of the cement had the shortest time of solidification. Then, the slurry was injected into grouting bag by the grouting pump.

(5) After recording the experimental data, the experiment was terminated.

The picture of the details of the experiment is illustrated in figure 7.

Figure 7. Photos of the prototype test.

By the observation of the experiment, the return trip was faster than the work trip, and the motion of the mechanism of propulsion was steady. The grouting support could hold up the pipe deflection of about 2–3 cm, and the support was reliable to solve the problem.
5. Conclusions
This paper shows the improvement in the traditional grouting support mode of construction work by developing the automatic grout bag-laying device instead of the diver. This reduces the risk in the project and improves the efficiency. According to the wave theory, it can be concluded that the wave load on the grouting support is less than the frictional force of the seabed on the support, and the grouting support is reliable for the submarine-suspended pipeline treatment project. Through the finite element method, it can be concluded that the deformation of the grout bag is elastic under the wave load, and sufficient toughness can meet the strength requirement. It was experimentally verified that the motion of the device was stable and reliable, and it could efficiently support the suspended pipeline to ensure the stability of the pipeline without breaking. Therefore, the scheme is feasible for engineering applications.

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