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On Lifting Axisymmetric Engineering Objects from a Poroelastic Seabed

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ABSTRACT

The problem of an axisymmetric engineering object detachment from a poroelastic water-saturated seabed is investigated. This involves the determination of forces which are required to release a body from the seabed and the corresponding times at which this occurs. The solution of the problem involves: (1) calculation of the displacements of the seabed, performed by employing an analytical solution to the Boussinesq problem, known from the theory of elasticity; and (2) analytical description of the evolution of the gap thickness and water pressure between the object and the seabed via applying the boundary layer approximation by Foda (1982). The proposed model is used to analyse two scenarios, in which time-histories of either the pulling force magnitude or the object vertical uplift velocity are prescribed. For both scenarios, breakout times and associated breakout forces are calculated for a range of parameters defining the elastic and hydraulic properties of the seabed; the results of these calculations are presented. The limit case of a rigid porous seabed is also considered.

Keywords: breakout phenomenon, poroelastic seabed, suction force, Boussinesq problem

INTRODUCTION

The mechanism for extricating engineering objects (such as caissons, ballast anchors, submarines, or sunken vessels) from the seabed is of growing interest to offshore, ocean and geotechnical engineering, the oil and renewable energy industry, foundation mechanics, and marine rescue services. It has long been known that the ‘lift-up’ forces required to detach an object from the sea floor may be of magnitudes which considerably exceed the submerged weight of the object. The object extrication mechanism involves the formation, and subsequent expansion, of a thin gap between the body base and the seabed surface, until a critical time when the body suddenly detaches (breaks out) from the bed; this time point is commonly referred to as the *breakout time*. The magnitude of the pulling force less the weight of the body at this characteristic time is referred to as the *breakout force*. Depending on the magnitude of the force required to detach a body from the seabed surface and, to a large extent, depending on the hydraulic properties of the underlying subsoil, the breakout time can be measured in hours or even days.

The phenomenon of the extrication of objects from the sea floor, and its analysis, first attracted the attention of engineers in the late 1960s [1, 12, 17]. At the beginning of the 1980s, two important papers were published by Mei [13] and Foda [6]. The first of these papers formulated a mathematical model describing the boundary layer in the seabed near its upper surface, based on the equations of the theory of consolidation for a poroelastic solid [2, 3]. The model formulated in [13] was then combined by Foda [6] with the theory of lubrication by Lamb [9], in order to describe the viscous fluid flow in a thin gap separating an object and the seabed. This complex theoretical framework was subsequently used by Foda [6] to derive approximate analytical solutions for the gap and then apply these equations to solve several engineering problems. More examples of the application of Foda's model can be found in two, more recent, papers by Michalski [15, 16], containing the results of calculations conducted for a wide range of parameters relevant to engineering practice. Foda's theory was further simplified by Mei et al. [14]; they assumed that the porous seabed was rigid (Foda considered the seabed to be deformable). An enhanced model based on the rigid bed approximation was developed three decades later by Chang et al. [4], in which it was assumed that the flow of the fluid in the gap was of the Stokes type. In another investigation, Sawicki and Mierczyński [18] proposed a theoretical model for describing the response of the deformable porous seabed at the initial stage of the breakout process (i.e. prior to the formation of a gap between an object and the seabed surface). The model equations were solved for one-dimensional and axisymmetric problems, in order to calculate suction forces arising in the subsoil and acting on an object's base.

The development of computer technology and numerical tools has made it possible to solve problems that cannot be treated by analytical methods. One example of this is the finite-element model by Zhou et al. [21], in which the spatial variation of gap thickness under an axisymmetric block was investigated. Another example is the finite-element model by Li et al. [10], in which the bearing capacity of a shallow strip foundation subjected to lifting forces was determined.

In parallel with theoretical and numerical investigations, experimental measurements were carried out to enhance our understanding of the breakout mechanism. Besides the above-quoted works by Muga [17], Liu [12] and Basiński [1], examples of early experiments were also reported by Mei et al. [14] and Foda et al. [8]. In the first of these experiments, the breakout forces of a rectangular plate were measured; while, in the second experiment, the forces acting on pipes laid on a seabed were investigated. Later, Sawicki and Mierczyński [18] conducted laboratory experiments on a disk, to determine the suction forces developing in water-saturated sand under an object. More recently, Chen et al. [5] and Li et al. [11] carried out a series of laboratory tests in a centrifuge, focusing on the measurement of suction forces acting on shallow foundations resting on clay.

In the present study, the breakout problem of axisymmetric engineering objects is analysed, similar to those investigated by Foda [6], Sawicki and Mierczyński [18], Zhou et al. [21] and Michalski [15]. Unlike these investigations, we introduce a new method to determine the displacements and, hence, the geometry of the free surface of a water-saturated poroelastic seabed under a rigid object. A fundamental analytical solution to the problem, known in the theory of elasticity as the 'Boussinesq problem' [19] which describes the behaviour of a half-infinite body under a point force, is employed, in order to determine the displacements of the seabed surface under the action of a pressure field developing under an object's base during up-lifting. The equivalent elastic properties of the water-saturated soil are derived from Biot's consolidation theory [3]. Having determined seabed displacements, the mechanism of generating negative (suction) pressures in water in the gap between the plate and the seabed is described by the equations derived by Foda [6]. The proposed model, combining the solution of the Boussinesq problem and Foda's gap, is used to simulate the breakout problem for a circular plate under two scenarios. In the first scenario, the time-history of the pulling force is given and, in the second, the time-history of the plate's vertical velocity is prescribed. For both scenarios, the times at which the breakout occurs and the associated breakout forces are calculated, and the dependence of the behaviour of the plate-seabed system on the soil's elastic and hydraulic parameters is investigated. Furthermore, the limit case of a rigid seabed is considered.

PROBLEM FORMULATION

The problem under investigation, depicted in Fig. 1, is solved in the cylindrical polar coordinate frame $Or\theta z$, with the vertical axis z directed upwards. The origin O of the coordinate frame is at the free surface of the seabed in its initial undeformed state, i.e. prior to the start of the upward movement of the engineering object from the bed. The object is modelled as a rigid circular plate (or block) of radius a, with its axis of symmetry coinciding with the coordinate axis z. With this choice of coordinates, due to the axial symmetry of the problem, all variables appearing in the analysis can be treated as independent of the angular coordinate θ.

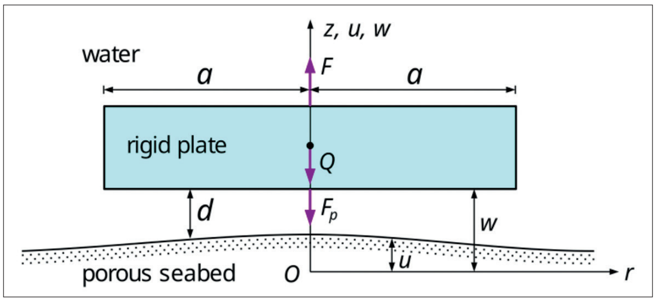

Fig. 1. Circular rigid plate of radius a, submerged in water, being lifted from a deformable porous seabed by a vertical pulling force F acting along the symmetry axis z. F_p is the suction force, Q denotes the apparent plate weight vector, w is the plate vertical displacement, u is the vertical displacement of the seabed surface and d denotes the thickness of the gap between the plate base and the seabed surface

The plate is subjected to the action of a vertical force $F(t)$, with t denoting time, which is lifting the object from the underlying seabed along the z-axis. The upward movement of the plate is resisted by a suction force $F_p(t)$, arising as soon as the plate starts to move. The suction force is due to two mechanisms. The first incorporates viscous effects arising in the fluid in the thin layer under the object base, as the water flows from the domain near the perimeter of the plate towards the domain under the central part of the plate base. The second mechanism involves the forces which resist the flow of pore water relative to the solid matrix of a seabed of low permeability, as the pore water filtrates out of the ground surface when the gap between the seabed and the object is widening.

The vertical displacement of the plate base is denoted by the function $w(t)$, with $w = 0$ at the initial time $t = 0$, and the vertical displacement of the seabed surface is denoted by the function $u(r, t)$, again with $u = 0$ at $t = 0$. These two displacements define the current thickness d of the gap between the plate base and the ground surface:

$$d(r, t) = w(t) - u(r, t), \qquad d \geq 0 . \tag{1}$$

The average seabed displacement U and the average gap thickness D are defined by:

$$U(t) = \frac{2}{a^2}\int_0^a u(r, t) r \,\mathrm{d}r ,$$
$$D(t) = \frac{2}{a^2}\int_0^a d(r, t) r \,\mathrm{d}r . \tag{2}$$

The motion of the object driven upwards by the pulling force F can be described by the equation:

$$M\ddot{w} = F - F_p - Q , \tag{3}$$

where M is the object mass, Q is the apparent weight of the object submerged in water (its own weight minus the buoyancy force), and the superposed dots denote time-differentiation. The inertia force represented by the left-hand side term in Eq. (3), with $\ddot{w}$ denoting the plate acceleration, can be regarded as negligibly small throughout a breakout event, except for a very short period of time when the object is abruptly detached from the seabed, immediately after the pulling force has overcome all the resisting forces in the dynamic system. The equation of motion (3) is solved for two cases. In the first case, the history of the pulling force $F(t)$ is prescribed and the plate displacement history $w(t)$ is calculated (which involves the calculation of the gap thickness and the seabed surface displacement, see Eq. (1)). In the second case, the plate vertical $v(t)$ is prescribed and the time variation of the forces $F(t)$ and $F_p(t)$, acting on the plate, are determined. In both cases, the time required to detach the plate from the bottom (the breakout time or the extrication time), denoted by t_b, is calculated. The scenario in which the plate velocity is prescribed, instead of the gap thickness-rate (as in the work of [6] and [15]), certainly seems to be a more realistic implementation for practical applications/measurements.

The suction force F_p in Eq. (3) is determined by the pressure field, denoted by $p(r, t)$, which is generated in the water filling the gap that develops between the ground surface and the plate base. Essentially, apart from the hydraulic properties of the seabed soil, the water pressure distribution in the gap depends on the current local gap thickness $d(r, t)$ and the time-rate of the gap thickness change $\partial d/\partial t$. The gap thickness, in turn, depends on the current plate base displacement $w(t)$ and the current local seabed displacement $u(r, t)$, as seen in Eq. (1). Since the latter displacement is a function of $p(r, t)$, acting on the porous seabed surface, one needs to solve the coupled problem for p and u in order to describe the evolution of the gap and the resulting suction force F_p.

GOVERNING EQUATIONS

In order to evaluate the seabed free surface displacement field $u(r, t)$, in terms of the current pressure field $p(r, t)$, the solution of the Boussinesq problem for an elastic half-space is used. Since the behaviour of a porous medium filled with water is being analysed, equivalent (representative) elastic parameters of the sand-water mixture must be determined. This can be done by employing the results known from the theory for poroelastic materials developed by Biot [2, 3], which express the soil properties in terms of the shear modulus of the soil matrix G, Poisson's ratio of the soil matrix ν, the volumetric porosity of the soil n, and the bulk modulus K of water filling the pores. These four parameters determine the equivalent Poisson's ratio of the water-saturated soil ν_e, as follows [6]:

$$\nu_e = \frac{1}{2}\left(\frac{2\nu}{1-2\nu} + \frac{K}{nG}\right)\left(\frac{1}{1-2\nu} + \frac{K}{nG}\right)^{-1}. \tag{4}$$

The shear modulus of the soil is the same as that of the solid matrix and the equivalent Young's modulus is $E_e = 2G(1 + \nu_e)$. Usually, the pore water contains bubbles of air, the presence of which leads to a considerable reduction in the bulk modulus of the water-air mixture compared to that of pure water K_0. This change in β is commonly described by the equation given in [20]:

$$\frac{1}{K} = \frac{1}{K_0} + \frac{1-S_r}{p_0} , \tag{5}$$

where S_r denotes the degree of saturation ($S_r = 1$ for no air presence in water) and p_0 is the pore water pressure (adopted as 100 kPa here, implying that the seabed is at a depth of about 10 m below the sea surface).

The Boussinesq problem is illustrated in Fig. 2. It consists of the determination of displacements in a semi-infinite, isotropic, linearly elastic body loaded by a single point force P applied at its free surface $z = 0$, acting along the direction normal to that surface. Although this is an idealised loading configuration, which is far from those encountered in civil engineering, the solution of the Boussinesq problem has good potential for solving problems of practical importance, owing to its analytic simplicity; this is demonstrated in this work.

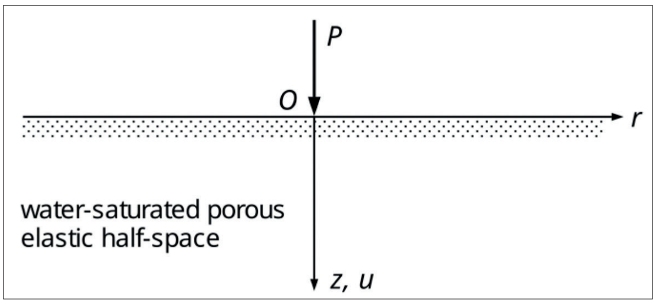

Fig. 2. Water-saturated porous elastic half-space loaded by a force P acting on the free surface z = 0 along the z-axis (the Boussinesq problem)

In the cylindrical polar coordinates (r, θ, z) shown in Fig. 2, the free surface vertical displacement field $u_P(r)$ in this radially symmetric configuration is given in terms of the force magnitude P and its distance r from a given point, as follows [19]:

$$u_P(r) = \frac{1-\nu_e}{2\pi G}\,\frac{P}{r}\,. \quad (6)$$

In order to determine the response of the semi-infinite half-space due to the water pressure acting in the gap under the object base, the contributions of elementary forces $dP = p(r, t)r dr d\theta$ are integrated over the whole plate base domain $r \leq a$, to yield the equation:

$$u(r, t) = \frac{1-\nu_e}{2\pi G}\int_0^a\int_0^{2\pi} \frac{p(r, t)}{\sqrt{r^2-2r\rho cos\theta+\rho^2}}\,\rho d\rho d\theta\,, \quad (7)$$

with ρ denoting a dummy radial coordinate. For the purpose of the description of the water pressure in the gap, presented below, one needs the average seabed displacement U under the plate, as defined by Eq. (2):

$$U(t) = \frac{2(1-\nu_e)}{\pi a^2 G}\int_0^a\int_0^a\int_0^{2\pi} \frac{p(r, t)}{\sqrt{r^2-2r\rho cos\theta+\rho^2}}\,\rho r d\rho dr d\theta\,. \quad (8)$$

We can now proceed to the description of the solution for the gap, using the results in [13] and [6]. Given the current position $w(t)$ of the plate base, the function $U(t)$ defined by Eq. (8) determines the current average gap thickness $D(t)$, see Eq. (1) and (2). Thus:

$$D(t) = w(t) - U(t)\,. \quad (9)$$

Now let us introduce the following functions [6]:

$$H(t) = \int_0^t \frac{dD}{d\tau}\,\frac{d\tau}{\sqrt{t-\tau}},\; L(t) = \int_0^t F_p(\tau)\,\frac{d\tau}{\sqrt{t-\tau}}\,,$$
$$\zeta(t) = \left(\frac{12\mu}{\alpha H D^3}\,\frac{dD}{dt}\right)^{1/2}, \quad (10)$$

where τ is the dummy variable of integration, μ is the water's dynamic viscosity, and α is the constant that accounts for the material parameters of the soil [6]:

$$\alpha = \frac{1+m}{m}\left[\frac{\rho_w g G/k_f}{\pi(1-2\nu)m+\pi(1/2-\nu)/(1-\nu)}\right]^{1/2},\; m = \frac{nG}{(1-2\nu)K}\,, \quad (11)$$

where ρ_w is the water density, g is the gravitational acceleration, and k_f is the soil permeability coefficient. With the functions in Eq. (10), the equations which govern the evolution of the suction force $F_p(t)$ and of the gap thickness $D(t)$ can be formulated as [6]:

$$F_p(t) = \pi a^2\alpha\left[1-\frac{2I_1(\zeta a)}{\zeta a I_0(\zeta a)}\right] H(t) \quad (12)$$

and

$$\frac{dD}{dt} = \frac{1}{\pi^2 a^2\alpha}\left[1-\frac{2I_1(\zeta a)}{\zeta a I_0(\zeta a)}\right]^{-1}\frac{dL}{dt}\,. \quad (13)$$

In the latter two equations, I_0 and I_1 denote the modified Bessel functions of the first kind, of the order zero and one, respectively.

NUMERICAL SIMULATIONS

The equations for plate motion, Eq. (3), gap expansion, Eq. (9), the evolution of the suction force in terms of the current gap thickness D, Eq. (12), and the evolution of D in terms of the current suction force F_p, Eq. (13), were solved numerically by a time-stepping scheme based on the forward Euler method. The length of the minimum time integration step necessary to achieve calculation convergence largely depended on the soil permeability coefficient k_f, varying between about 1.0 s for $k_f = 10^{-7}$ m/s to about 0.01 s for $k_f = 10^{-3}$ m/s. It was assumed that, at the initial time $t = 0$, the plate-seabed system was in static equilibrium and the plate and seabed displacements, w and u, were zero.

Two scenarios of object lifting were simulated. In the first one, the pulling force history $F(t)$ was prescribed while, in the other, the plate vertical velocity $v(t)$ was given. Smooth variations of these two functions were adopted and the pulling force variation defined by the equation in Foda's numerical simulations [6];

$$F(t) = F_m\,\frac{t}{t + t_0}\,, \quad (14)$$

where F_m is the magnitude of the pulling force at $t \to \infty$, and $t_0 > 0$ is the parameter (it can be seen that $F(t_0) = F_m/2$). This idealised smooth variation of $F(t)$ is illustrated in Fig. 3.

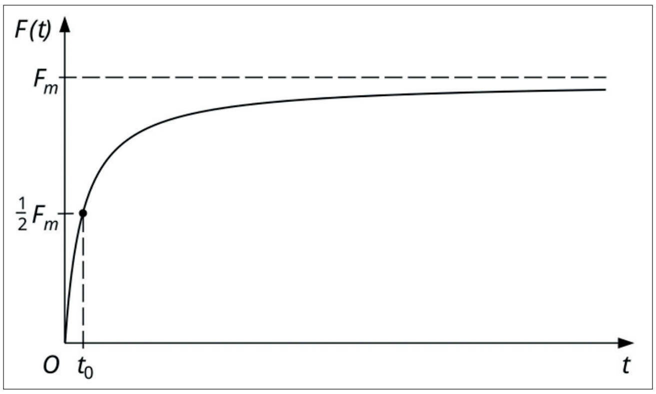

Fig. 3. Idealised smooth time-variation of the pulling force F(t) adopted in the simulations

By analogy to Eq. (13), the time-variation of the vertical velocity of the plate $v(t) = \dot{w}(t)$, was adopted in the similar functional form:

$$v(t) = v_m\,\frac{t}{t + t_0}\,, \quad (15)$$

where v_m is the limit magnitude of the plate velocity and t_0 is the time at which $v = v_m/2$. The velocity in Eq. (15) requires the vertical displacement of the plate to be defined by

$$w(t) = v_m\left[t - t_0\ln\left(\frac{t + t_0}{t_0}\right)\right], \quad (16)$$

which is derived by the time integration of the relation in Eq. (15). In fact, the function $w(t)$, not $v(t)$, is the one used as input in the numerical simulations.

The calculations were performed for a plate of radius $a = 5$ m and thickness $h = 0.4$ m, assuming that it was made of concrete of a density $\rho_b = 2.4 \times 10^3$ kg/m^3. The parameters defining the sandy seabed were: shear modulus $G = 1 \times 10^7$ Pa, Poisson's ratio $\nu = 0.3$ and porosity of soil $n = 0.4$. The parameters for water filling of the pores were: bulk modulus $K_0 = 2.15 \times 10^9$ Pa and dynamic viscosity $\mu = 1.31 \times 10^{-3}$ Pa · s. The soil permeability was defined by the coefficient of permeability k_f, with its values ranging from 10^{-7} m/s to 10^{-3} m/s; $k_f = 10^{-5}$ m/s was considered a typical value.

The results for the case of the prescribed pulling force time-variation $F(t)$, defined by Eq. (14), are presented, after adopting Foda's [6] time constant $t_0 = 1$ s. The plots in Fig. 4 illustrate the gap thickness evolution $D(t)$ at different limit magnitudes of pulling force F_m, for fully-saturated ($S_r = 1.0$) sand with the coefficient of permeability $k_f = 10^{-5}$ m/s. The plot shows that, independent of the magnitude of the driving force, the gap between the object base and the seabed remains very thin throughout the whole breakout event, with the average gap thickness D increasing very slowly, up to values typically not exceeding 10^{-4} m. The rapid increase in D only occurs within a very short period of time, immediately preceding the instant of the full detachment of the object from the seabed, when the respective curves in the plots become almost vertical. The times when this occurs mark the breakout times t_b for the given pulling forces F.

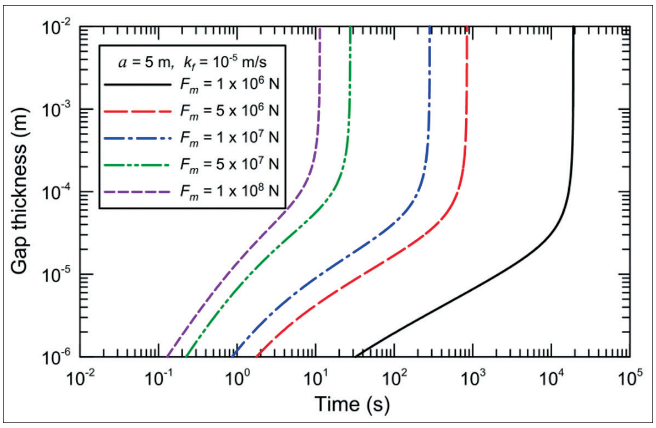

Fig. 4. Gap thickness evolution D(t) as a function of pulling force magnitude F_m for fully water-saturated ($S_r = 1$) soil with a coefficient of permeability $k_f = 10^{-5}$ m/s ($a = 5$ m, $G = 10^7$ Pa, $\nu = 0.3$, $n = 0.4$)

Figure 5 illustrates the effect of the soil permeability on the development of the gap under the plate base. Hence, for the force $F_m = 10^7$ N, the variation of the gap thickness $D(t)$ for different values of the coefficient of permeability k_f is shown. It can be seen that, when plotted on the logarithmic scale, the breakout times t_b decrease with increasing values of k_f, in a regular manner, with $t_b = 2769$ s for the least permeable seabed ($k_f = 10^{-7}$ m/s) and $t_b = 32$ s for the most permeable seabed ($k_f = 10^{-3}$ m/s).

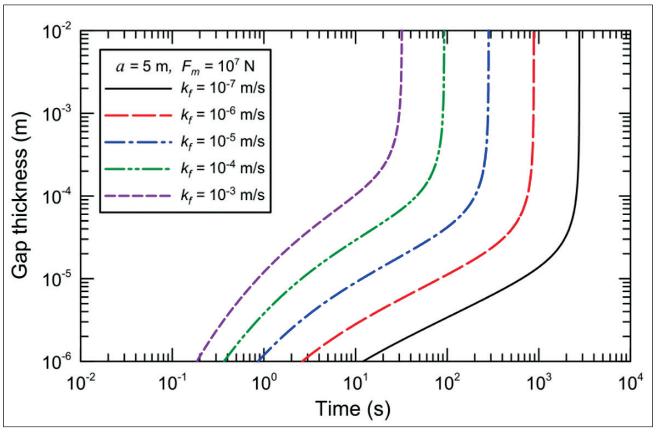

Fig. 5. Gap thickness evolution D(t), for the fixed pulling force magnitude $F_m = 10^7$ N, as a function of the coefficient of permeability k_f ($S_r = 1$)

Figures 4 and 5 present the results for fully water-saturated sand, where $S_r = 1.0$. The plots in Fig. 6 illustrate the effect of the partial saturation of soil pores on the gap thickness evolution $D(t)$. The presence of even a very small amount of gas in the pore water results in a dramatic decrease in the breakout time t_b for a given magnitude of the pulling force F_m. A gas content of just 1% in the pore water ($S_r = 0.99$) leads to a breakout time reduction of approximately 882 s (full saturation) to a mere 13 s (for the illustrated selected case of $F_m = 10^7$ N and $k_f = 10^{-6}$ m/s).

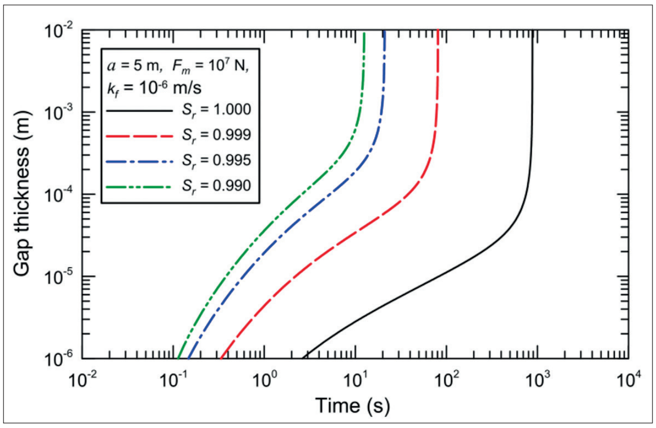

Fig. 6. Gap thickness evolution D(t) under a plate lifted by the force $F_m = 10^7$ N as a function of the degree of saturation S_r for the soil with a coefficient of permeability $k_f = 10^{-6}$ m/s

In turn, Fig. 7 demonstrates the effect of the soil strength, represented by the shear modulus G, on the plate extrication mechanism. The breakout time monotonically decreases with the increasing strength of the seabed. The limit case of a perfectly rigid soil (short dashed line) is also plotted in the figure.

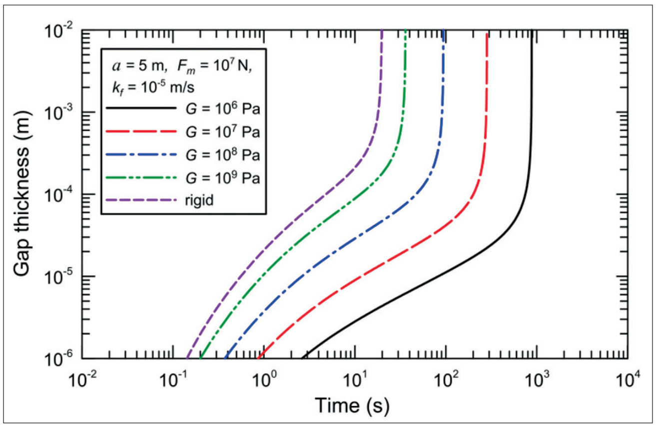

Fig. 7. Gap thickness evolution D(t) under a plate lifted by the force $F_m = 10^7$ N, as a function of the shear modulus G of the seabed ($k_f = 10^{-5}$ m/s, $S_r = 1$)

The plots in Fig. 8 illustrate the variation of the plate breakout time with the pulling force magnitude F_m as a function of the soil permeability coefficient k_f, for the fully water-saturated soil. In the log-log coordinates, the plotted curves are approximately straight lines, with the same slope gradients.

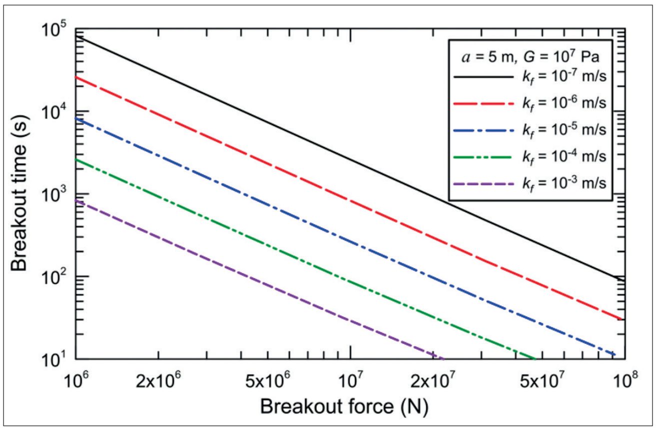

Fig. 8. Dependence of the plate breakout time on the pulling force magnitude F_m and the soil permeability coefficient k_f, for the fully water-saturated sandy seabed (a = 5 m, G = 10^7 N, S_r = 1)

The following four figures present the results obtained for the second scenario analysed, in which the plate is lifted at a prescribed vertical velocity $v(t)$, as defined by Eq. (15), with the time parameter t_0 = 1 s being adopted again. The plots in Fig. 9 illustrate the evolution of the suction force $F_p(t)$ acting under the plate base, depending on the limit values of the vertical plate velocity v_m. It can be seen that the peak values of the suction forces, defining the magnitudes of the respective breakout forces F_b, regularly increase with increasing plate uplift speed v_m, when plotted on the log-log axes. Similarly, the values of the associated breakout time t_b, defined by the almost vertical sections of the curves, also decrease regularly with increasing v_m (in log-log coordinates). The plots in Fig. 9 correspond with the curves displayed in Fig. 10, showing the time-growth of the gap thickness $D(t)$ as a function of the plate uplift velocity v_m. Qualitatively, the curves resemble those in Fig. 4, plotted for different pulling force magnitudes F_m, although it should be noted that the gap thickness growth-rates are now significantly larger. The characteristic upper ends of the curves for the two smallest velocities v_m (the solid and long-dashed lines) correspond to situations where the detachment of the plate from the seabed is fully completed, so that the rate of increase of the gap thickness becomes equal to the vertical velocity of the plate v_m.

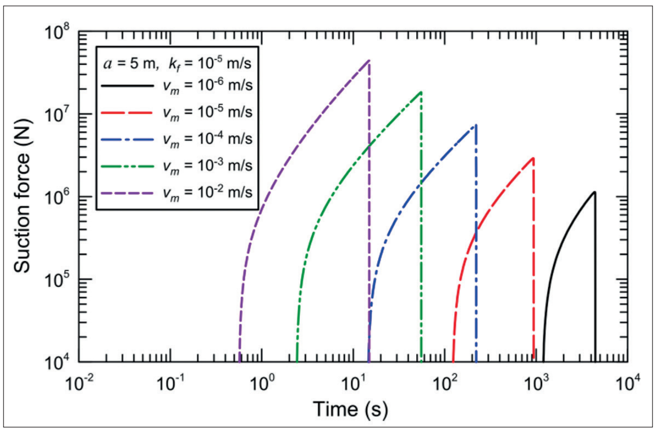

Fig. 9. Suction force evolution $F_p(t)$ for a plate of radius a = 5 m as a function of the limit plate uplift velocity v_m (k_f = 10^{-5} m/s, S_r = 1)

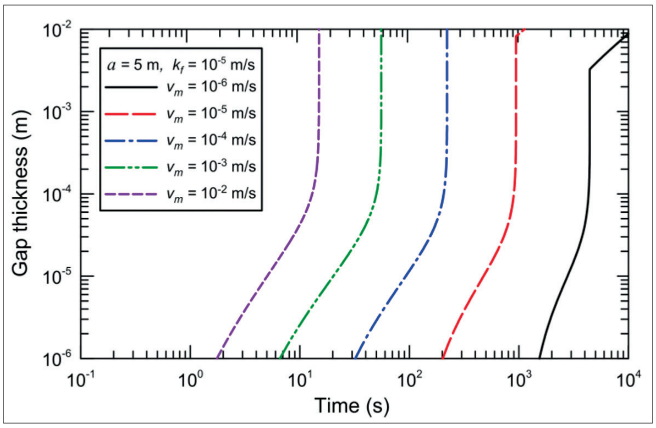

Fig. 10. Gap thickness evolution $D(t)$ as a function of the limit plate uplift velocity v_m (k_f = 10^{-5} m/s, S_r = 1)

Fig. 11 illustrates the evolution of the suction force $F_p(t)$ acting under a plate that is moving upwards at a constant velocity v_m = 10^{-4} m/s, as a function of the soil permeability defined by the coefficient k_f. Somewhat unexpected results were predicted by the model, which showed all the curves almost following the same path, independent of the soil permeability, all the way up to the respective breakout time t_b when the curves become almost vertical, reflecting the abrupt reduction of the suction forces to near-zero values.

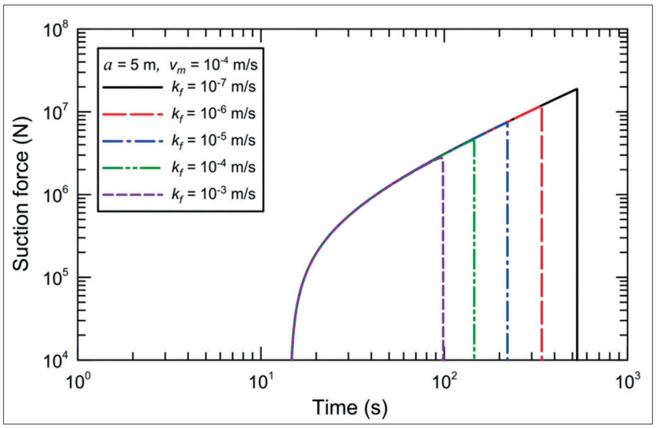

Fig. 11. Suction force evolution $F_p(t)$ for a plate of radius a = 5 m as a function of the coefficient of permeability k_f state (S_r = 1)

Finally, corresponding with the previous figure, the plots in Fig. 12 demonstrate how the gap thickness $D(t)$ evolves with changing values of the soil coefficient of permeability k_f.

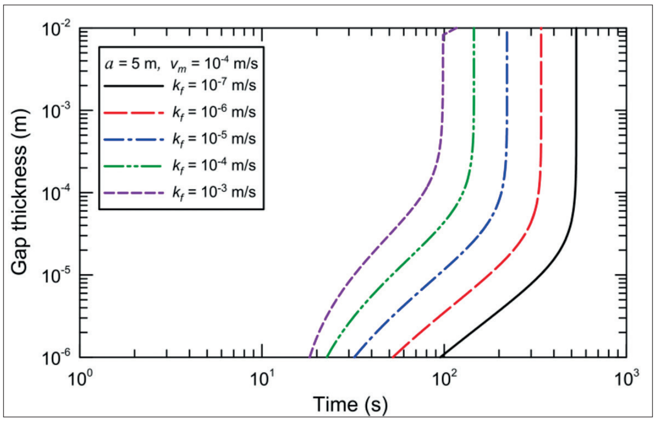

Fig. 12. Gap thickness evolution D(t) for a plate lifted with the velocity $v_m = 10^{-4}$ m/s as a function of the coefficient of permeability k_f ($S_r = 1$)

CONCLUSIONS

The problem of lifting an axisymmetric object from the surface of a water-saturated sandy seabed was investigated. The problem was solved by combining: (1) the analytical solution of the Boussinesq problem for an elastic half-space, to determine displacements of the seabed surface, which is a completely novel approach to this type of problem, and (2) the approximate solution for the water flow and pressure field inside the gap separating the object base and the seabed surface, after Foda [6].

The proposed model accounts for seabed deformability and was applied to simulate the breakout mechanism of a rigid circular plate for two scenarios, in which either the pulling force history was prescribed or the vertical plate velocity history was defined. The main focus was on the calculation of the maximum values of the breakout forces and the associated breakout times, depending on the mechanical and hydraulic parameters of the seabed. The results of the numerical simulations carried out for the two scenarios illustrate the dependence of the breakout time and the breakout force on the limit magnitude of either the pulling force (the first scenario) or the plate vertical velocity (the second scenario). The predicted values of the breakout time vary over a very wide range, from seconds to hours, depending on the size of an object and the magnitude of either the pulling force F_m or the pulling velocity v_m, as can be seen in the presented plots. All of the results show that the soil permeability coefficient k_f plays a major role. For a fixed pulling force F_m (the first scenario), an increase in this coefficient by four orders of magnitude (from 10^{-7} m/s to 10^{-3} m/s) results in a decrease in breakout time by about two orders of magnitude (see Fig. 5 and Fig. 8). In the second scenario, for a fixed value of the vertical velocity of the plate v_m, the same increase in the soil permeability coefficient (by four orders of magnitude) reduces the breakout time by about one order of magnitude (see Fig. 11 and Fig. 12) A significant role is also played by the degree of saturation of the pore water; its reduction from 1.00 to 0.99 leads to a decrease in the plate breakout time by approximately two orders of magnitude.

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