Off-road mobility assessment based on seismic bearing capacity

Evaluation de la mobilité hors-route basée sur la capacité portante sismique

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ABSTRACT

In the events that require rapid mobilization of off-road vehicles, it is crucial to have a method that would allow the quick evaluation of the possibility of vehicle mobility in off-road conditions. Accordingly, this paper proposes a method that is based on the limit equilibrium of soil under the loading conditions imposed by an accelerating vehicle. The goal is to reduce the problem to the familiar bearing capacity problem and to introduce mobilization factors that are based on the vehicle, soil, topography and motion variables. This is achieved by adapting seismic bearing capacity equations to vehicle-soil interaction problems.

RÉSUMÉ

Pour les cas, qui demandent une mobilisation rapide des véhicules hors-route, il est crucial d'avoir une méthode qui permettrait une évaluation immédiate de la possibilité de la mobilité du véhicule dans les conditions hors-route. En parallèle, cet article propose une méthode qui est basée sur l'équilibre limite du sol dans les conditions du chargement imposées par un véhicule qui accélère. Le but est de réduire le problème en problème familier de capacité portante et d'introduire les facteurs de mobilisation qui sont basés sur le véhicule, le sol, la topographie et les variables du mouvement. On traite ce problème en adaptant les équations de capacité portante sismique aux problèmes d'interactions véhicule-sol.

Keywords : Seismic bearing capacity, dynamic fluidization, vehicle-soil interaction, mobilization

1 INTRODUCTION

Vehicle-soil interaction problem is a broad subject that considers vehicle characteristics, soil-vehicle interaction, soil behavior, and topography. Therefore, in cases such as militaristic emergencies when immediate mobilization of forces is required, rapid evaluation of off-road vehicle mobility becomes necessary. For that reason this study proposes a method that adapts seismic bearing capacity analyses for assessing the possibility of off-road vehicle mobility.

Soil-vehicle interaction requires the consideration of loading from the vehicle and the effects of varying topography. In this study, loading from the vehicle is being regarded as the loading from a footing and topographical effects are formulized within the framework of dynamic fluidization (Richards et al. 1990). Thus, the problem is being reduced to a seismic bearing capacity problem. Therefore by adapting seismic bearing capacity analysis, the problem is being considered as a limit state problem and the decision is given on a "go or no go" basis. Explicitly, the problem is being regarded as an extraordinary bearing capacity problem of a footing resting parallel to a slope which is under the action of an inclined load. Accordingly, the tracks or the wheels of a vehicle correspond to the footings of a structure, the combination of the vehicle weight and traction loads correspond to the inclined loading, and the slope of the ground corresponds to the ratio of the horizontal to vertical seismic accelerations. The geometry of the failure surface is being defined using the fluidization assumptions.

This paper describes the fluidization concept, after which its application to seismic bearing capacity problems will be summarized. Following, soil-vehicle interaction mechanism will be evaluated and formulated using limit equilibrium methods. Finally, equations describing the load transfer at the vehicle-soil interface will be combined with seismic bearing capacity equations to come up with mobility equations which are used to evaluate the possibility of mobility under the presumed circumstances such as the ground inclination, soil strength parameters, vehicle characteristic, and vehicle acceleration. However, owing to the limited extent of this paper only four-wheeled off-road vehicles are considered. The analysis of tracked vehicles is explained in detail by Cagbayir (2008).

2 SEISMIC BEARING CAPACITY ANALYSIS BASED ON FLUIDIZATION CONCEPT

Even though dynamic fluidization mechanism has originally been developed for mechanically understanding the causes of several earthquake failures such as movements of retaining structures and tilting of buildings, the assumptions that form the basis of the fluidization concept are much better suited to identify vehicle mobility problems. Accordingly, off-road vehicle mobility is analyzed by adapting appropriate seismic bearing capacity mechanisms which are based on the fluidization concept.

2.1 *Dynamic fluidization concept*

Fluidization is concerned with the effects of earthquake accelerations on horizontally layered uniform soil layers (Richards et al. 1990). Fluidization concept has several underlying assumptions. It is assumed that the soil is a homogeneous horizontal half-space, soil behavior is perfectly plastic, earthquake accelerations have constant uniform horizontal and vertical components, and these earthquake accelerations are imposed on the soil as static forces that are constant and unchanging throughout the depth of the half-space. It is proposed that the imposed earthquake accelerations will change the state of the soil when a critical threshold value is exceeded. Thus, flow will be possible within a bounded range of directions which in turn will dictate the geometry of the possible mechanism of bearing failure.

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Mohr-Coulomb stress space is used to quantify the effects of accelerations on the stress states of homogeneous horizontal soil layers. As a result the static stress field in the principal stress plane x-z can be formulated as (Richards et al. 1990)

$$\sigma_z = \gamma z \tag{1}$$

$$\sigma_x = K\gamma z \tag{2}$$

$$\tau_{zx} = 0 \tag{3}$$

where z is the depth, γ is the unit weight, and K is the coefficient of lateral earth pressure. If horizontal and vertical uniform accelerations are imposed on the same layer, the stress state is calculated, with an effect similar to the so-called shear beam, as (Richards et al. 1990)

$$\sigma_z = (1-k_v)\gamma z \tag{4}$$

$$\sigma_x = K(1-k_v)\gamma z \tag{5}$$

$$\tau_{zx} = -k_h\gamma z \tag{6}$$

where k_h and k_v are the ratios of horizontal and vertical earthquake accelerations to the gravitational acceleration. Figure 1 depicts effects of k_h and k_v on the stress state of the soil. Point A in the figure corresponds to the stress state acting on a horizontal plane under static conditions that is quantified by Equations 1 and 3. If at this state, a uniform constant vertical acceleration equal to $k_v g$ acts on the soil layer, the Mohr circle shrinks in size for which the stresses acting on the horizontal plane are depicted using point B. As it can be observed, Mohr circle is still bounded by the K_o lines since there is no shear stress. The stresses at point B are shown by Equations 4 and 3. Finally, if in addition to the vertical acceleration $k_v g$, horizontal acceleration $k_h g$ is imposed on the ground Point B moves to Point C and the Mohr circle increases in diameter about a fixed center since horizontal acceleration imposes pure shear effect. Point C represents the stress state on a horizontal soil layer which corresponds to Equations 4 and 6. In Figure 1, k_h value has been chosen such that the Mohr circle has touched the failure envelope. At this state shear flow can occur along the slip planes. The orientations of the slip planes are dependent on the strength characteristics of the soil, magnitudes of stress at which the failure line is reached and can be calculated using the origin of planes construction (Figure 1).

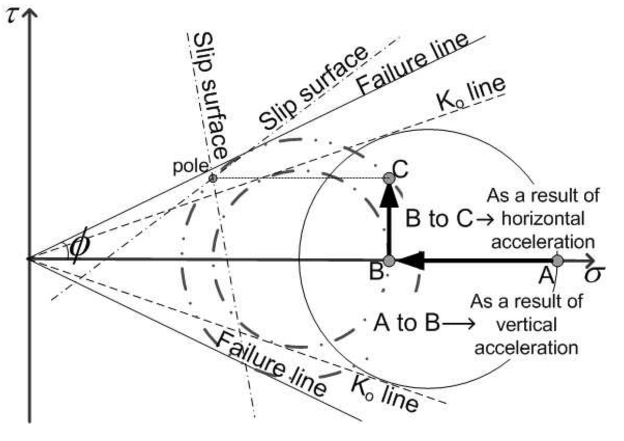

Figure 1. Effects of accelerations on the stress state of soil elements.

The geometry of the failure mechanism during bearing capacity analysis depends on the orientations of the slip planes. As the intensity of the horizontal acceleration increases, coefficients of lateral earth pressure increase since the Mohr circles cannot increase in diameter by crossing over the failure lines. As a result the orientations of the slip planes start to approach horizontal, thus resulting in shallower failure mechanisms. Therefore there is a critical link between the earthquake accelerations, especially the horizontal acceleration, and bearing capacity of foundations.

As previously stated, in fluidization analysis earthquake accelerations are assumed to have constant uniform horizontal and vertical components. This assumption is based on the famous Mononobe-Okabe analysis (Mononobe 1929). In studies based on fluidization, the dynamic effect on the soil element is calculated using the ratio of horizontal acceleration to vertical acceleration. This ratio is represented by θ and considers also the gravitational acceleration:

$$\theta = \tan^{-1}\left(\frac{k_h}{1-k_v}\right) \tag{7}$$

The size and position of the Mohr circle representing the stress state of a unit soil element depends on tanθ.

2.2 *Seismic bearing capacity*

For the case in this study, from the methods that have been reviewed, Fishman et al. (2003) method has been found to be the most appropriate. The reasons for this choice are that it is simple and it is based on fluidization concept rendering the consideration of both the soil inertia forces and vehicle loading feasible. Fishman et al. (2003) assumes a Coulomb wedge type of failure surface as shown in Figure 2. The advantage of using Coulomb type of failure surface is the inherent simplicity which is gained by eliminating the fan-shaped transition zone. As a result the interface between the active and the passive wedges is assumed to act as a retaining wall concentrating the shear transfer between the wedges. Shi and Richards (1995) proposed using an angle of friction between the wedges as $\delta=\phi/2$. When this value is used for the imaginary wall friction, the end results are very close to the ones obtained from the failure mechanisms that have fan-shaped transition zones.

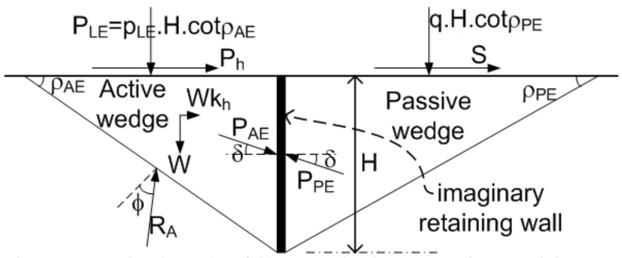

Figure 2. Coulomb wedge failure mechanism according to Fishman et al. (2003).

In classical foundation engineering applications, the effects of inclined loading on the bearing capacity are calculated empirically. But in Fishman et al. (2003) method the influence of inclined loading is incorporated into the limit equilibrium equations, making it possible to extend the solution of bearing capacity problem to dynamic cases. This is similar to the problem of defining shear forces transmitted from a vehicle to the ground. As shown in Figure 2, Fishman et al. (2003) assumed that at the instance of failure active force, P_{AE}, and passive force, P_{PE}, are coaxial, equal in magnitude but opposite in direction. P_{AE} can be calculated by constructing the equations of equilibrium for the active wedge in the horizontal and vertical directions. Solving and arranging the two equations of equilibrium for P_{AE}, we get (Fishman et al. 2003)

$$P_{AE} = \left(\frac{2p_{LE}}{H} + \gamma\right)\frac{H^2}{2}R_1 + \frac{1}{2}\gamma H^2 k_h R_2 + np_{LE}H\tan\phi R_2 \quad (8)$$

where γ is the unit weight of soil, $n=P_h/(P_{LE}\tan\phi)$ is a parameter that represents the reduction in the bearing capacity due to the shear at the footing and the active wedge interface and parameters R_1 and R_2 are defined as (Fishman et al. 2003)

$$R_1 = \frac{\sin(\rho_{AE} - \phi)\cot\rho_{AE}}{\cos(\rho_{AE} - \phi - \delta)} \quad (9)$$

$$R_2 = \frac{\cos(\rho_{AE} - \phi)\cot\rho_{AE}}{\cos(\rho_{AE} - \phi - \delta)} \quad (10)$$

Fishman et al. (2003) calculated P_{PE} using the lateral earth pressure theory:

$$P_{PE} = \frac{1}{2}\gamma H^2 K_{PE} + qHK_{PE} \quad (11)$$

where K_{PE} is the seismic coefficient of lateral earth pressure. The value of K_{PE} can be calculated using the Mononobe-Okabe analysis (Mononobe 1929). At the time of failure $P_{AE}=P_{PE}$, so using Equations 8 and 11 and arranging for p_{LE} which is shown in Figure 2, we get

$$p_{LE} = q\left(\frac{K_{PE}}{R_1 + n\tan\phi R_2}\right) + \frac{1}{2}\gamma B\left(\frac{K_{PE} - R_1 - R_2 k_h}{R_1 + n\tan\phi R_2}\tan\rho_{AE}\right) \quad (12)$$

As a result, the seismic bearing capacity factors are obtained as

$$N_{qE} = \frac{K_{PE}}{R_1 + n\tan\phi R_2} \quad (13)$$

$$N_{\gamma E} = \frac{K_{PE} - R_1 - R_2 k_h}{R_1 + n\tan\phi R_2}\tan\rho_{AE} \quad (14)$$

Due to insufficient number of equations, the value of the critical angle ρ_{AE} is found by iteration. Since at failure active thrust is at its maximum value, ρ_{AE} is the angle giving the maximum K_{AE}. Derivation of the bearing capacity factors are given by Fishman et al. in detail. Because this method of solution relies on the Mononobe-Okabe analysis, which is developed for cohesionless soils, calculating N_{cE} is not possible. There are several suggested ways of calculating N_{cE}. One way is to calculate N_{cE} using a different failure mechanism, such as Budhu and Al-Karni (1993) method, which also relies on the fluidization concept. The other method, as suggested by Richards et al. (1993), is to employ the relationship given by Terzaghi (1943) without any real justification and calculate N_{cE} from N_{qE}:

$$N_{cE} = \frac{N_{qE} - 1}{\tan\phi} \quad (15)$$

In this paper none of these methods are opted for since the goal is to introduce the methodology of analyzing the vehicle-soil interaction using seismic bearing capacity concepts.

3 ADAPTING SEISMIC BEARING CAPACITY ANALYSIS TO MOBILITY PROBLEMS

Vehicle-terrain interaction should be defined separately for different types of vehicles, considering wheeled or tracked. However, in this paper, only four-wheeled off-road vehicles will be considered. Since the problem is a difficult soil-structure interaction problem several simplifying assumptions are required. First of all, pressure distribution is considered uniform and solved using plane-strain approach. As a result, the vehicle weight under plane-strain, w_v, is obtained as

$$w_v = W_v/2E \quad (16)$$

where W_v is the weight of the vehicle, and E is the width of the wheel into the plane of drawing (Figure 3). Moreover, tire sinkage into soil is ignored and the tire-soil interface is modeled as a rectangular contact area. These are appropriate assumptions that stay on the safe side.

Figure 3 illustrates the forces acting on a wheel. The forces imposed on the ground are not equally distributed between the wheels and this distribution depends on the slope of the ground, dimensions of the vehicle, and the position of the center of gravity of the vehicle. This problem can easily be solved using the equilibrium of forces in Figure 3. Accordingly in the analysis of mobility, the wheel under the greater load, called the critical wheel, will be considered. In the case shown in Figure 3 where the vehicle is accelerating up a slope, the critical wheel corresponds to the rear wheel.

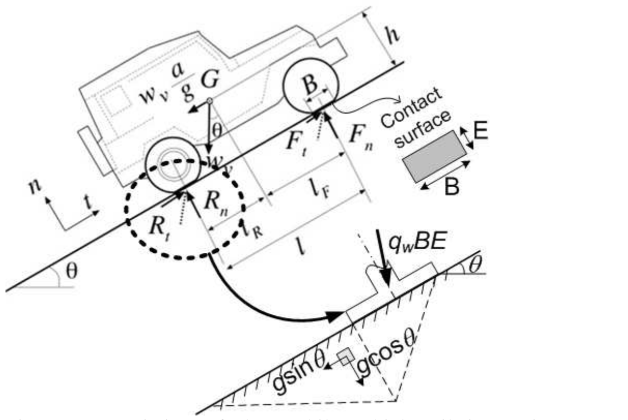

Figure 3. Depiction of the mobile vehicle-soil interaction as an extraordinary footing on a slope.

As shown in Figure 3, the normal and tangential components of the reaction force on the front and rear wheels constitute four unknowns. These unknowns can be solved by writing four equations of equilibrium in the direction normal to the slope, parallel to the slope, by taking the moment about a point, and by assuming that the resultant forces at the front and rear wheels have the same inclination. Solving for the uniform inclined stress q_w exerted through the critical wheel, we obtain components that are normal, $(q_w)_n$, and parallel to the slope, $(q_w)_t$, as (Cagbayir 2008; Cagbayir and Cinicioglu 2008)

$$(q_w)_n = \frac{w_v\cos\theta}{B}k \quad (17)$$

$$(q_w)_t = (q_w)_n\, i \quad (18)$$

where i is the inclination of q_w. Parameter i can be calculated from the equations of equilibrium as (Cagbayir 2008)

$$i = \left(\tan\theta + \frac{a}{g\cos\theta}\right) \quad (19)$$

and k is a parameter that defines the vehicle characteristics. Parameter k (Cagbayir 2008) depends on the kind of vehicle, such as tracked or wheeled. For wheeled vehicles

$$k = \frac{l_F + hi}{l} \tag{20}$$

One interesting feature of vehicle mobility analysis is, as shown in Figure 3, the equivalency between the acceleration ratio of the fluidization concept as given in Equation 7 and the slope angle of the ground surface. That is why parameter θ is used for representing both phenomena. As it can be seen in Figure 3, the gravitational acceleration acting on a unit soil element resting in a slope can be divided into two components; acceleration component parallel and acceleration component normal to the slope. These acceleration components are equivalent to k_h and $(1-k_v)$, respectively.

For the complete analysis of off-road mobility problem, the other mechanism that should be investigated is the slipping at the vehicle-soil interface. Within the bounds of the contact problem which is simplified as a result of explained assumptions, the shear stresses exerted to the ground through the wheels are limited by the shearing resistance at the interface. The evaluation of the slipping mechanism is explained in detail by Cagbayir (2008).

4 BEARING CAPACITY EQUATION FOR MOBILITY

The solution for the bearing capacity equation for mobility is obtained by adapting the Fishman et al. (2003) mechanism to the mobility problem, as shown in Figure 4.

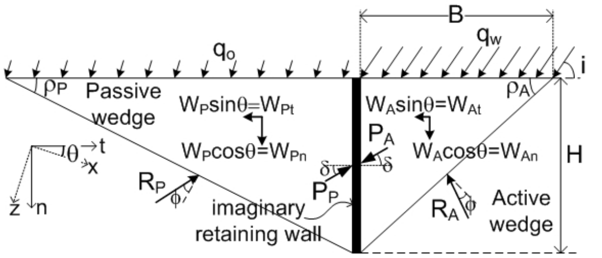

Figure 4. Coulomb wedge mechanism adapted to mobilization problem.

Writing the equations of equilibrium in the horizontal and vertical directions for the active wedge and arranging, we get

$$P_A = \left[\frac{1}{2}\gamma H^2 \sin\theta + i\left(q_w\right)_n H\right]R_1 + \left[\frac{1}{2}\gamma H^2 \cos\theta + \left(q_w\right)_n H\right]R_2 \tag{21}$$

where

$$R_1 = \frac{\cos\left(\rho_A - \phi\right)\cot\rho_A}{\cos\left(\rho_A - \phi - \delta\right)} \tag{22}$$

$$R_2 = \frac{\sin\left(\rho_A - \phi\right)\cot\rho_A}{\cos\left(\rho_A - \phi - \delta\right)} \tag{23}$$

Passive thrust, P_P, can be calculated as in the case of Equation 11 in which the lateral earth pressure is calculated using Mononobe-Okabe analysis. Using the failure condition $P_A=P_P$, and writing the equilibrium equation using Equations 11 and 21 and arranging for the ultimate vehicle contact stress, $(w_v)_{all}/B$, we get

$$\frac{\left(w_v\right)_{ult}}{B} = qN_{qm} + \frac{1}{2}\gamma BN_{\gamma m} \tag{24}$$

where

$$N_{qm} = \left(\frac{K_P}{k\left(R_1 + iR_2\right)\cos\theta}\right) \tag{25}$$

$$N_{\gamma m} = \left(\left[\frac{K_P - R_1\sin\theta - R_2\cos\theta}{\left(R_1 + iR_2\right)\cos\theta}\right]\frac{\tan\rho_A}{k}\right) \tag{26}$$

are the bearing capacity factors for mobilization. In order to calculate N_{qm} and $N_{\gamma m}$, it is necessary to calculate the angle of rupture for the active wedge, ρ_A, by iteration. Since $P_A=P_P$ at failure, ρ_A is the angle giving the maximum value of K_A.

Finally calculated values of the bearing capacity factors for mobility (N_{qm} and $N_{\gamma m}$) are used to calculate the ultimate vehicle weight, $(W_v)_{ult}$, that can travel with the considered acceleration values on the slope of certain inclination and strength characteristics. Considering the vehicle has four wheels with rectangular contact areas and inserting shape factors s_q and s_γ (to modify the problem from plane-strain to rectangular area) into the equation, we get

$$\left(W_v\right)_{ult} = \left[qN_{qm}s_q + \frac{1}{2}\gamma BN_{\gamma m}s_\gamma\right]4BE \tag{27}$$

5 CONCLUSIONS

In this paper the seismic bearing capacity equation is modified to mobility problems in order to be able to evaluate the possibility of mobility of wheeled vehicles in off-road conditions. This is achieved by proposing an equation that yields the ultimate vehicle weight that can travel at a given acceleration on a given slope of known strength characteristics. This equation can be adjusted to yield ultimate acceleration values, slope angles, or strength properties when the other properties are known.

Cagbayir (2008) prepared a computer code that decides on the mobility limits of vehicles on given topographical conditions. Moreover, the results obtained from the computer code can be prepared in the form of mobilization charts that allows the rapid identification of the mobility limits of certain vehicles for considered topographies.

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