WTIV Touch-Down Loads on Hard Seabeds

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ABSTRACT

Offshore wind farms (OWFs), especially those in shallow waters and consisting of monopile and/or jacket foundations, have been growing rapidly over the past few years. By the end of 2026, Europe is expected to have installed up to 105 GW of new wind energy capacity. Many more OWFs are being developed as a part of the efforts towards a carbon-neutral plan by 2050.

Development of OWFs has installation challenges and every site is characterized by unique geotechnical and hydrodynamic conditions that offer both risks and opportunities for designers, consultants, operators and contractors. A particular risk is the existence of rocky outcrops that substantially influence the installation routines of wind turbine generator (WTG) components.

Going on Location (GoL) touch-down loads on the legs (spudcans or pads) of Wind Turbine Installation Vessels (WTIVs) does not pose significant risk in soft seabeds. However, when a hard seabed is present, there may be significant dynamic forces which may easily exceed the allowable load limits advised by the WTIV designer.

Published GoL work has mostly been done on medium to stiff soils (such as clay and sand). The present study focuses on the impact loads between the legs of a WTIV and seabeds that are mostly void of granular material and instead described as bedrock. As such, this article aims to improve the technical understanding of the impact loads WTIV legs experience when very hard seabeds are encountered. To this effect, an impact model is proposed and presented to predict the range of the dynamic loads during touch-down. The model integrates hydrodynamic motions of the free-floating WTIV into a coupled (or "two-way dynamic") model accounting for the structural stiffness of the legs, as well as a non-linear seabed. The characteristics of the hard seabed and the effects of WTIV motions, mass and spudcan/pad geometry on the touch-down loads are discussed.

KEY WORDS: Jackups, WTIVs, Jackups, Going on Location, Impact Model, Spudcans/Pads

INTRODUCTION

Every OWF site has unique geotechnical characteristics and time-dependent environmental conditions that may pose risks and opportunities to the design and installation of WTGs. One of the key aspects, on which few studies have been performed, is the risks associated with the existence of rocky outcrops on site [3, 2]. Rocky outcrops are found on the seabed in different parts of the continental shelves, ranging from the Sea of Japan and the South China Sea in the East and in the English Channel and the Bay of Biscay in Europe [12, 13, 10, 5]. This article attempts to cover the implications induced by the presence of rocky outcrops (sometimes also referred to as bedrock) from the installation point of view by means of improving the technical understanding on the nature of the impact that occurs between the WTIV's leg/spudcans and the seabed.

For sites where relatively soft seabeds are encountered, WTIV touch-down does not induce substantial risk, as the low stiffness of the seabed, combined with its damping effects produce relatively low impact loads on the WTIV's legs/spudcans. For these sites, environmental limits for GoL operations may be dictated by other parameters as opposed to the structural limitations of the WTIV. In other words, when the pads/spudcans collide soft seabeds, the momentum exchange between the WTIV and the seabed is associated with relatively large soil deformations over relatively long duration before coming to a stop – hence, the impact loads are low. However, in the case of hard seabeds, the momentum exchange occurs in a relatively short time between two relatively stiff objects, resulting in large impact loads. These loads are dynamic in nature and mostly act on the WTIVs as shock impulses. The dynamic nature of the shock and the existence of a wide variety of the parameters influencing the magnitude of the force caused the mechanism of the impact not to be fully understood and sometimes leading to the overlooking of associated risks.

A few studies such as those by Daun and Olson in 2014 [2] and by Donh et al in 2013 [3] and Mille et al [19], attempted to investigate the issue with static and pseudo-static methods based on the principle of conservation of energy. The work by Daun and Olson [2] lacks the dynamic aspects of the impact. The work by Donh et al [3] accounts for velocity effects but lacks the influence of the geometrical shape of the impacting objects, stiffnesses and/or failure of the seabed material. Miller et al [19] integrated vessel motions and a hydrodynamic model with a structural model of the leg/spudcan. However, they modelled the seabed by linear springs where no plastic deformation was allowed.

More recent works by Drake [22], Drake and Zhang [23], Vazquez et al [18, 14, 17], Tan et al [20] and Chang and Liu [21] focused on the coupled effects of the seabed and jack-ups, and accounted for jacking speed, spudcan shape and the phasing of the response of each of the legs. OrcaFlex [7] was used in these models, based on excitation load RAOS as well as added mass/damping coefficients and multiple contact elements to represent the spudcan shape to mimic a target leg penetration curve (which ignores soil dynamic effects) while also accounting for the eccentric load imparted by the soil when the leg is not perfectly vertical. In these studies, the spudcan load vs penetration curve was not linear, but the seabed was modelled as being elastic and offered no damping to the response of the jack-up. The 2017 work by Vazquez et al expanded the analyses to add a post-response review of the effects of modeling the seabed using combined Lagrangian-Eularian method to model the seabed. In this model, the spudcan had prescribed motions and the seabed was allowed to have plastic deformation. The results showed the benefits of modeling the seabed properly.

PROPOSED MODEL

For clarity, it is noted that the proposed model is intended for sites with very stiff or hard seabeds usually referred to as bedrock and void of granular material. While bedrock may conjure visions of impenetrable material, in this context the expectation is that there will be some leg penetration upon the local failure and breakage of the bedrock (if any). Therefore, the initial model has no voids, but after contact/impact, a failure zone will develop producing rock fragments and allowing for the leg's tip to penetrate below the original seabed level.

Given that a single WTG usually has its foundation installed prior to the tower/nacelle/blades and given that a typical offshore wind farm is made up of several dozen WTGs, the number of times a WTIV must transition from the afloat condition to the elevated condition (via Going on Location operations) at the different WTG locations can reach or exceed a hundred. For sites with stiff seabeds and with non-negligible seastates, these operations expose the WTIV to impact loads that could damage the legs and/or jacking system. Therefore, it is important to understand the mechanism of impact occurring between the seabed and WTIV legs.

The touch-down of a WTIV on the hard or stiff seabed is an interdisciplinary topic where structural, hydrodynamics and geotechnical engineering interface. In this paper, an impact model to predict the range of the dynamic forces may induce on WTIV legs during the touch-down on the stiff seabed is proposed within an interdisciplinary framework.

To further elaborate, a WTIV arrives at a location and depending on the hydrodynamic conditions at the site at the time of the jacking operation, undergoes translational and rotational oscillatory motions. Given the rigidity of the WTIV, the vessel motions and velocities can be used to establish the motions and velocities at the WTIV leg tips. Then, depending on the WTIV characteristics and the hydrodynamic conditions, a range of possible vertical and horizontal combinations of impact velocities are determined and used to feed the structural and seabed models. The structural model defines the stiffness of the legs as well as the distribution of the masses throughout the WTIV body (i.e., preserving inertia matrix of the system). The ground model defines the response of the seabed and determines mobilized resistance against the impact. The full model is described in Figure 1.

As can be seen in Figure 1, there is a loop of action and interaction in such a way that the first impact can influence the motion of the vessel and hence, the second and third cycles of WTIV leg impact can be studied. The sections below present further details.

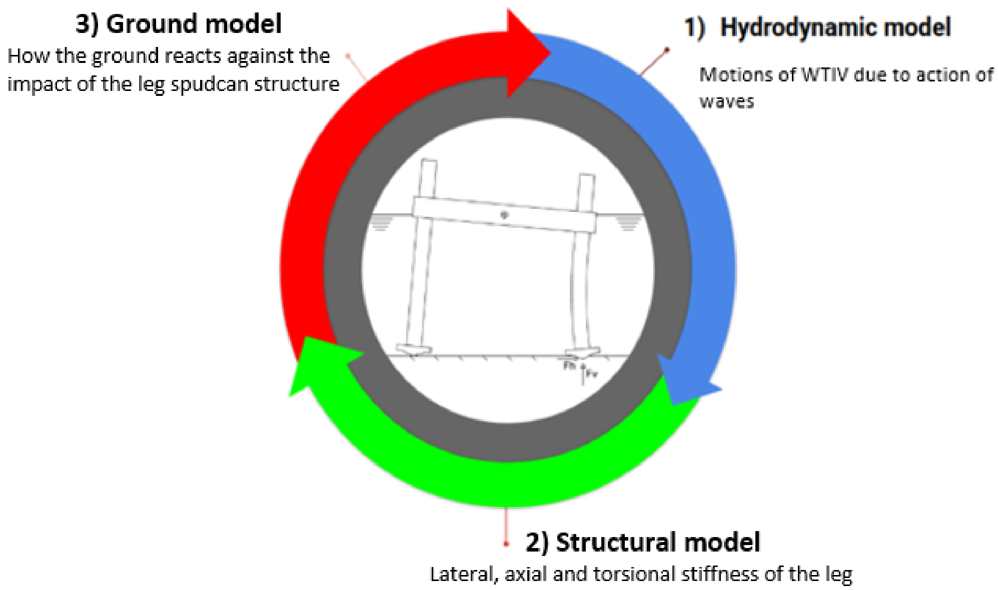

Figure 1: WTIV's leg impact on stiff seabed: interfaces of hydrodynamics, structural and geotechnical aspects (Interior figure reproduced from DNVGL-RP-C104 [15])

HYDRODYNAMIC MODEL

In the presence of waves, the WTIV undergoes translational and rotational oscillatory motions. Different WTIVs have different responses to the same wave conditions, as the mass, size and geometry affect both the wave loads and response of every unit. The vessel loads, hydrodynamic coefficients (added mass/damping) and free-floating motions can be calculated with acceptable accuracy using available commercial software [11, 7]. To feed the impact model, it is vital to determine a range of possible horizontal and vertical velocities (V_H and V_V) of the tip of WTIV legs.

Assuming regular waves, the WTIV's free-floating response is also regular in nature. Then, the WTIV tip leg motions form an elliptical path on which the horizontal and vertical velocities reach their extreme values at the middle of the peak-to-peak displacement, as shown in Figure 2 (where A_H and A_V represent horizontal and vertical motion amplitudes, respectively).

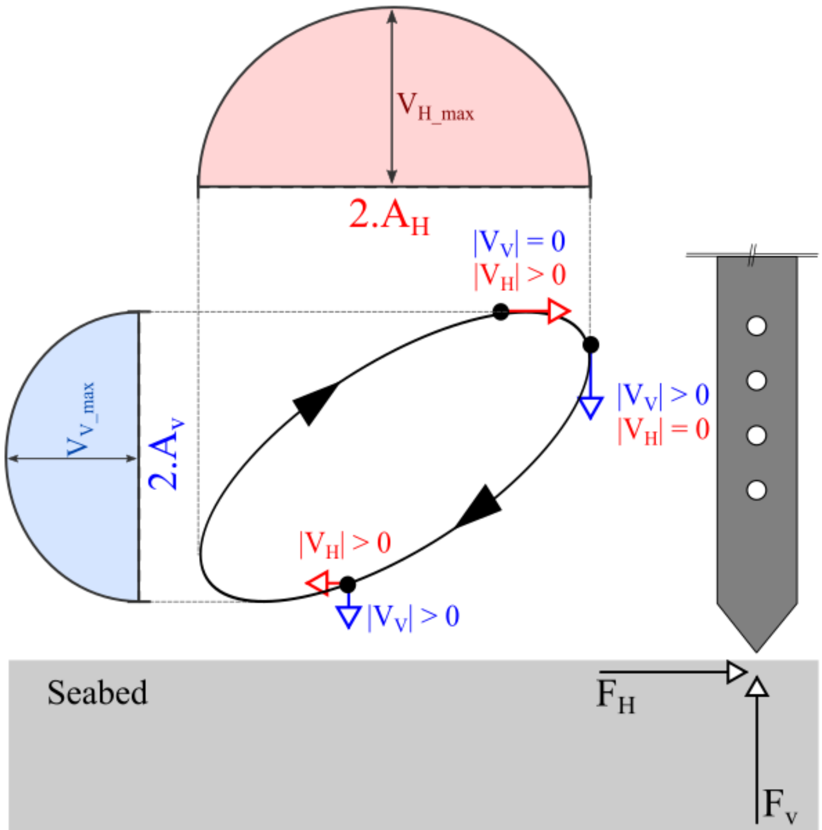

Figure 2: WTIV leg tip cyclic motion (in Free-Floating Mode and Prior to Impact with the Seabed)

It is noteworthy that the vertical and horizontal velocities are not the only influencing factor on the induced horizontal and vertical forces on the WTIV leg tip. The geometrical shape of the tip plays a determining role in this regard (see section below). Additionally, the phasing of the motions of all other legs also plays a role.

STRUCTURAL MODEL

In the structural model, the stiffnesses (horizontal, axial and twist) of the legs as load-carrying elements derived through FEM or analytical approaches and they are used to integrate to the ground model for the impact resolution. This is schematically shown in Figure 3. It is illustrated in Figure 3 that the leg stiffnesses are used to constraint a rigid body model of leg tip (or spudcan) to the vessel hull. Besides, the mass distribution on the board of WTIV can be accounted in the model to correctly accumulate the inertial twisting effect around the impacting leg. In such scheme, there is no need to model the entire system of water, vessel, legs and ground in one computationally expensive model (regardless of the implementation complexity) to conduct the impact resolution.

It was noted that the point of the structural model is to consider the structural stiffnesses of the legs and to introduce structural damping to the impact resolution. In other words, the inclusion of the structural model in the system would lead to slightly reducing the level of the loads by extension of the impact duration. Hence, skipping the structural model would lead to a conservative level of forces. In addition, in the WTIVs with rigid tubular legs, the magnitude of the stiffnesses is sufficiently large (as compared to WTIVs with truss legs) and will have less damping effect on the impact loads. As a result, skipping the structural model for WTIVs with thick and rigid tubular legs might be trivial.

There might be additional damping due to the interaction of racks and pinions in the jacking house; however, due to the uncertainties around the application mechanism, it is conservatively recommended to be disregarded.

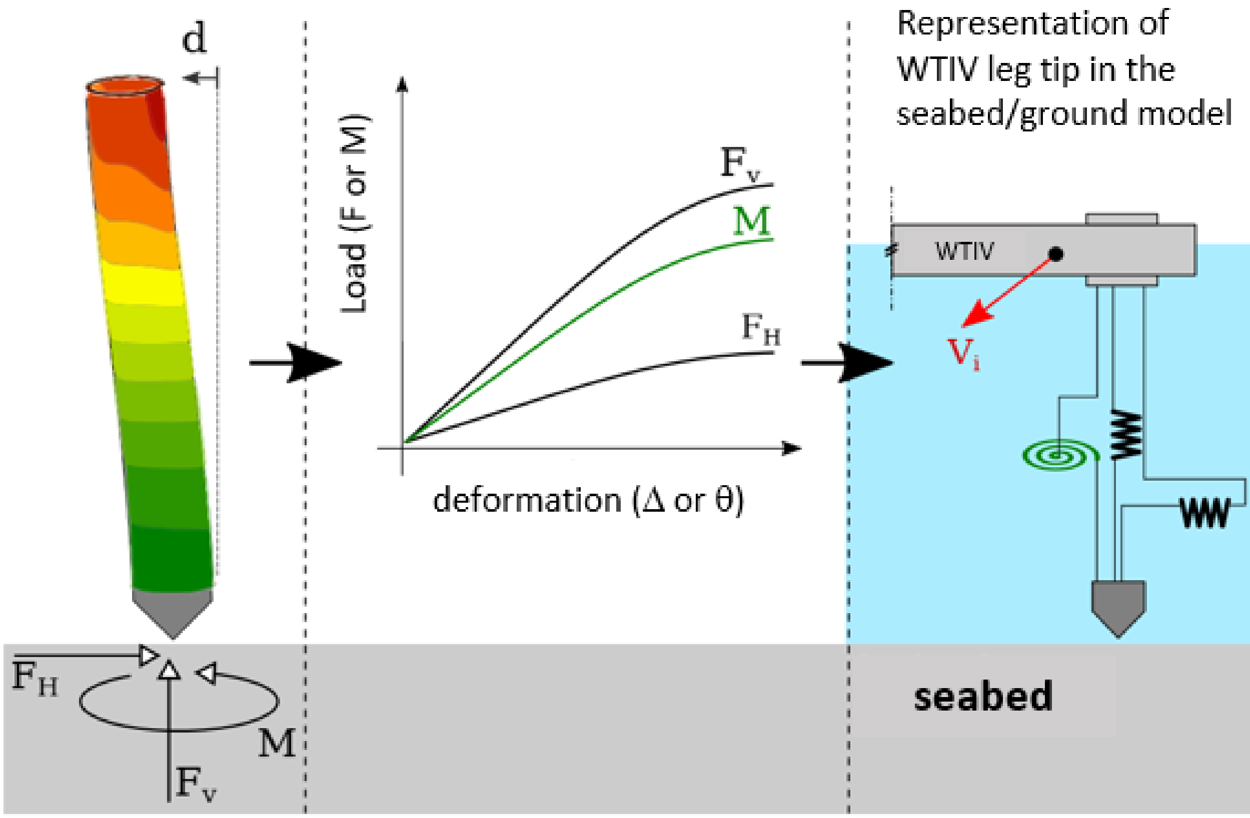

Figure 3: Derivation of Axial, Horizontal and Rotational Leg Stiffness

SEABED MODEL

The basis of the ground model is Contact Dynamics [6, 8], in which the rock fragments are modelled as rigid objects. This approach is well suited for granular simulations where most of the deformations are categorized as plastic deformations (such as rotation and relative translational movement of rock particles with respect to each other) [6].

In the ground model, the seabed is discretized into randomly shaped polyhedrons (rigid objects). An example of the ground domain discretization is shown in Figure 4. In this model, neighboring polyhedrons are bonded together, and a breaking threshold is defined by the multiplication of the input ground strength with the contact area of the pair of neighboring polyhedrons. The size of the fragments should be small enough to allow the rock to fail along its weakest potential failure plane. However, polyhedrons can adopt a larger size when they are located far from the impact zone. In the case of failure in the rock, each polyhedron or a failed block consisting of several polyhedrons interact as rigid objects with the neighboring objects (representing crushed fragments of rock in size of boulders, pebbles or gravels).

The ground model used for this study has been validated against numerous laboratory UCS and PLT testing on rock cores from several rock outcrops found in OWFs in Europe.

The proposed ground model introduces a two-way fully dynamic analysis between the leg tip and the ground. The term "two-way" means both WTIV and bedrock are influenced by the impact, while in one-way dynamic analysis, the movement (or integrity) of the impacting object is not influenced by the impact.

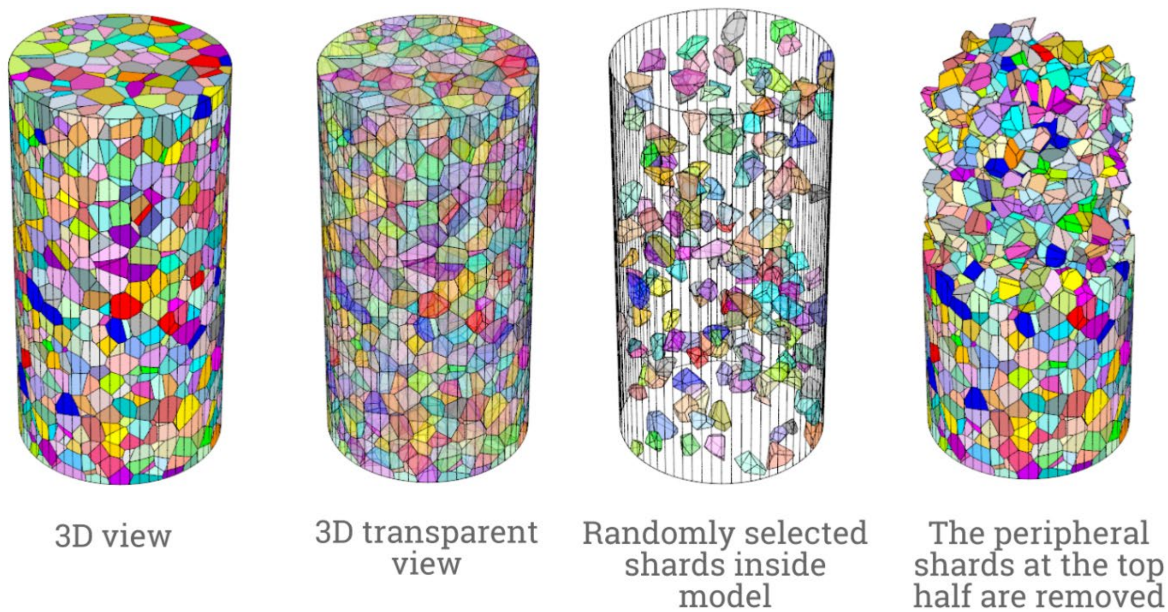

Figure 4: Morphology of a Discretized Cylindrical Sample

UNDERSTANDING IMPACT

This section briefly presents the mechanics of impact and serves as a basis for the rest of the study. To this aim, let us assume an impact between a rigid, stationary plate and an elastic disk with a specific colliding velocity. Velocity changes before and after the impact multiplied by the mass of the disk deliver the impulse. An impulse (I) is defined as:

$$I = \int_{t_1}^{t_2} F dt = m_{disk} \Delta v = m_{\ disk}(v_2 - v_1)$$

Where, F is the impact force, m_{disk} is the mass of the disk, t_1 and t_2 are the time points at the beginning and end of the impact, respectively. Likewise, v_1 and v_2 represent the velocity of the disk before and after impact. The impact duration and force can vary depending on the impacting velocity and the stiffness of the disk. To further clarify, the impact of a disk with radius and Elastic Modulus of 4cm and 100MPa, respectively onto a rigid plate is numerically modelled and studied. The disk has an initial downward velocity of 1m/s and positioned 1mm above the rigid plate and is subject to the gravitational acceleration. The impact force and the kinetic energy of the disk are monitored. The impact simulation repeated for two other cases: once the Elastic Modulus of the disk doubled (denoted as 2xE); and then the disk with the base case Elastic modulus (100MPa) modelled but this time with a failure strength of 200kPa (denoted as $E_{plastic}$) where the disk would behave as elastic-perfectly plastic material and allows to investigate the effect of plastic failure on the force-time records of the impact. The latter case can give us a general indication of how the bedrock failure can affect the impact force (this is demonstrated and further studied in the next sections). The force vs time and kinetic energy vs time plots illustrated in Figure 5. Figure 6 shows the Strain on the disks at impact.

As shown in the plots, increasing the Elastic Modulus of the disk results in shorter impact duration, and increase in the peak impact force up to around 35%. However, changing the material behavior from full elastic to elastic-perfectly plastic with the failure strength of 200kPa would change the scheme of the force and kinetic energy time records. The material failure of the disk tends to increase the impact duration which results in the significant kinetic energy loss, and that is why the restitution response observed in the full elastic disks (E and 2xE cases) is not observed in the $E_{plastic}$ case.

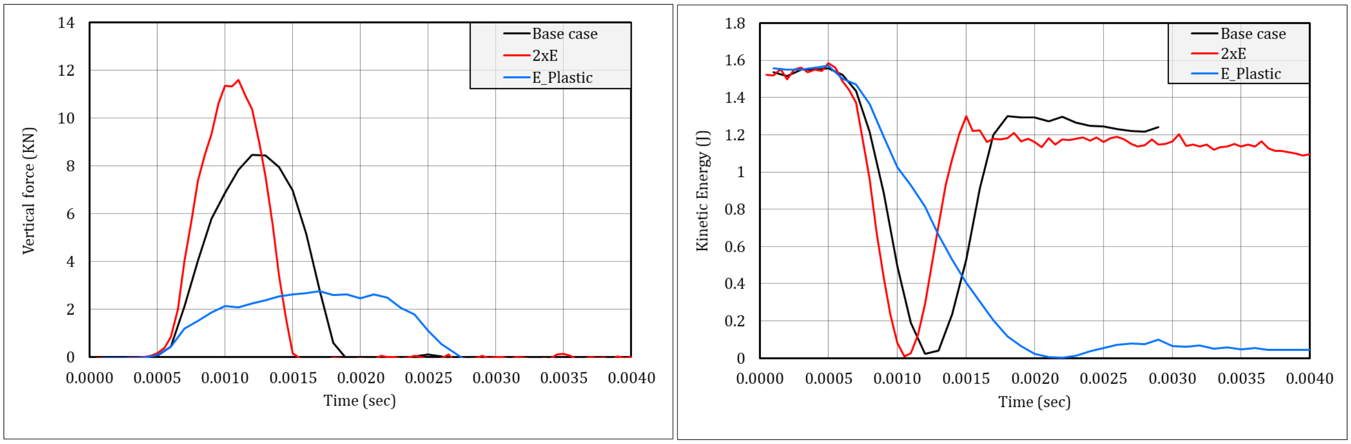

Figure 5: Impact Force and Kinetic Energy Records of the Disk During the Impact

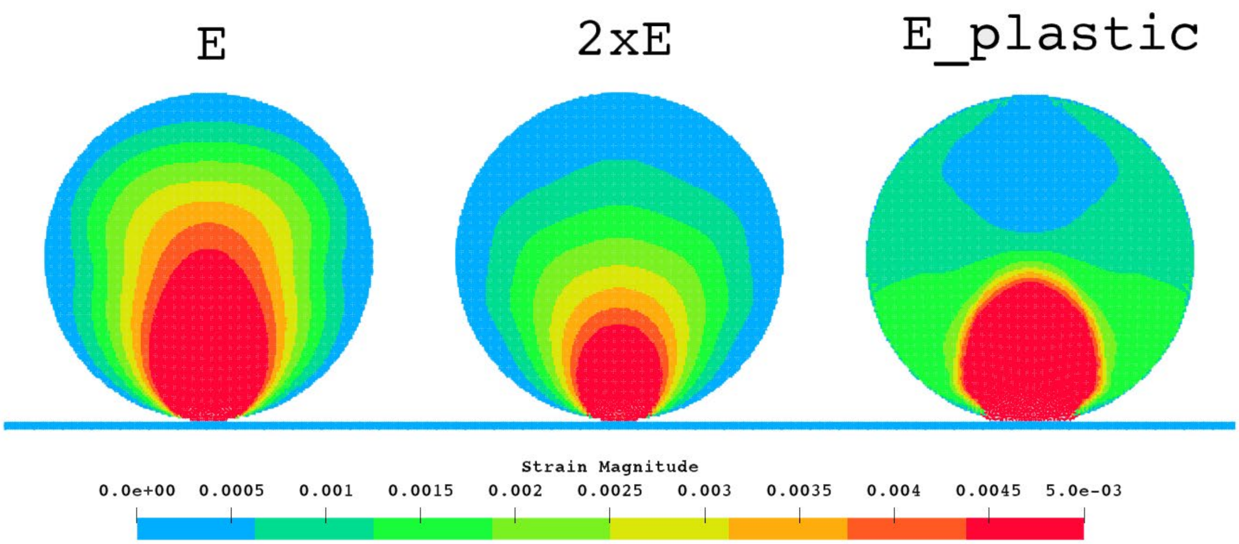

Figure 6: Effect of Elastic Modulus on Strain of the Disk During at Impact

The disk impact example serves as a basis for a better understanding of the nature of the impact. There are still additional parameters influencing the impact characteristics such as mass and the geometry of the impacting objects. The latter has a principal effect on the magnitude of the force. These parameters investigated in the next sections where the impact of WTIV leg or spudcan evaluated through numerical modelling.

PARAMETRIC STUDY

This section presents the results of a parametric study on the impact of WTIVs leg onto hard seabed through numerical models by assessing various parameters influencing the impact force magnitudes such as the geometry of leg tip, the mass of the WTIV, impacting velocity and strength of the rock. The focus of the parametric study is the derivation of the impact forces when the seabed is represented as breakable rock and to determine how the elastic and plastic characteristics of the rock can influence the dynamic horizontal and vertical impact loads. Below is the numerical model information:

- It is conservatively assumed that the touch-down occurs on a single leg of the WTIV. This is a reasonable assumption since there are always uncertainties concerning the motion of the vessel.

- The base case WTIV leg tip downward vertical and horizontal velocities of 0.5m/s and 0.25m/s presumed. The ratio of horizontal to vertical velocity was kept constant in all the analyses.
- The tip of the WTIV leg, regardless of the geometry, was positioned 5cm above the bedrock
- The bedrock discretized in such a way that the rock fragments around the impact zone have an average diameter of 5cm as the distance from the impact zone increased, the rock fragments can have a larger average diameter.
- Regardless of the leg tip geometry, the legs are assumed to have a tubular shape with a diameter of 3.0m with considerable thickness.
- The influence of the leg stiffnesses are not taken into consideration (i.e., rigid legs).

At the very beginning of the simulation, the initial vertical and horizontal velocities applied to the WTIV leg, and the vertical and horizontal forces, displacements and the velocity of the leg is monitored.

To facilitate the comparison of results, the plotting range on all like-graphs is kept uniform, and all graphs for the parametric study are presented at the end of this section.

EFFECT OF LEG TIP GEOMETRY

To investigate the effect of the shape of the leg tip on the forces, two leg tip geometries as shown in Figure 7. The spudcan consists of a 12.0m diameter cylinder with a pointed shape at the bottom with a conical offset of 1.0m while the conical leg is a cone attached at the bottom of the 3.0m diameter leg with the conical offset of 1.0m. Obviously, despite the fact both shapes share the same conical offset, the tip angles (also referred to as attacking angle) are different. The conical tip of both shapes was tapered in such a way that upon the touch-down a small area of the leg tip is in contact with the seabed.

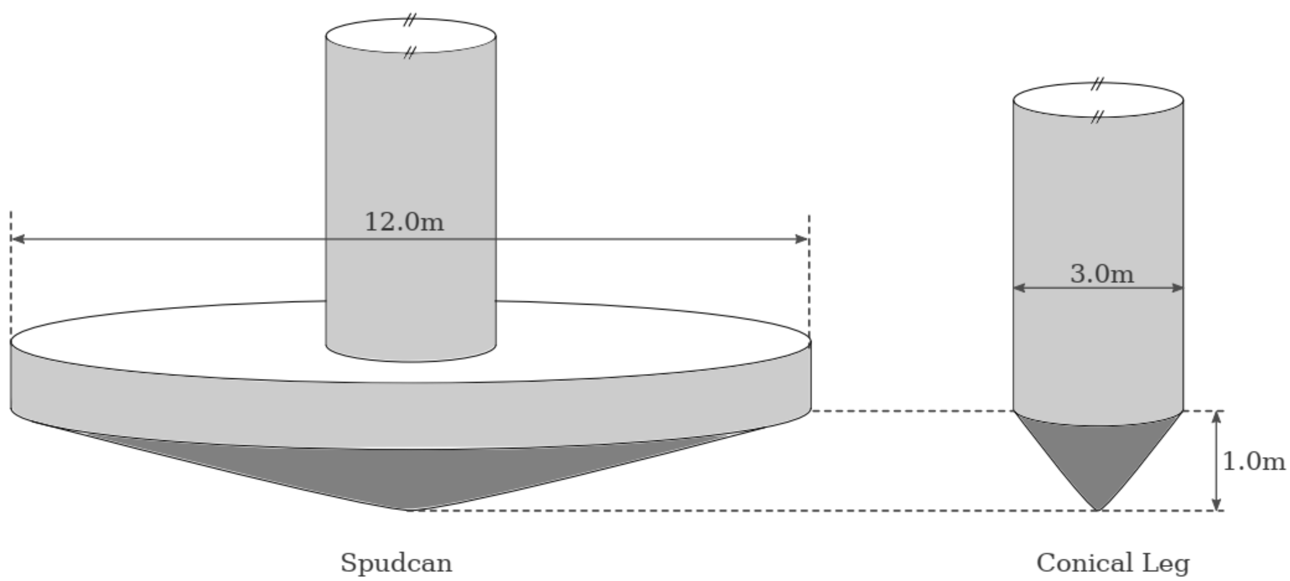

Figure 7: Two Investigated WTIV Leg Tip Geometries: Spudcan (left) and Conical Leg (right)

As can be seen, the conical leg delivers slightly longer impact duration and smaller peak vertical dynamic force. The penetrations of the leg tip in both cases were less than 4cm, although the conical leg geometry shows a slightly larger penetration. The records of the leg velocities of the impact show the recovery of at least 99% of the impacting velocities meaning that a negligible impact energy loss occurred due to minimal cracking or breakage of the bedrock around the impact zone. The horizontal forces acting on the legs in both cases were less than 4.0MN.

EFFECT OF IMPACT VELOCITY

The influence of the impacting velocities investigated by doubling the initial impacting velocities. All the other parameters were kept unchanged. The data for the base impacting velocities also are plotted for comfortable comparison for each case. For the spudcan case, the results show a larger penetration and the development of a larger vertical force up to 160MN as compared to the base velocities. The force records of the spudcan with doubled velocity indicates that the bedrock mostly behaves elastically, although again minimal kinetic energy loss due to the rock cracking is detected. This is mainly due to the larger impact area of the spudcan as compared to the conical leg. In the case of the conical leg shape, the increase in the vertical impact forces does not follow the same trend as observed in the spudcan case. The vertical force vs penetration graphs of the conical leg show that with doubling the impact velocity, the larger penetration observed followed by the fluctuating vertical forces which indicate the local breakage of the bedrock. This observation confirmed by the recovery percentage of the impacting velocity of 61%. In other words, 39% of the kinetic energy of the conical leg with doubled impacting velocity dissipated due to the local breakage of the bedrock at the impact zone.

Monitoring the horizontal forces show a substantial increase in the case of the conical leg (up to 27MN) while the horizontal forces in the spudcan almost remained unchanged compared to the base impact velocities. Regarding the penetration of the leg tips into the bedrock, the mobilization of large horizontal forces can be explained by the fixity of the leg tip in the rock mass.

EFFECT OF WTIV MASS

As noted in Equation 1, the magnitude of the mass of the impacting object directly influences the impulse and the impacting force. In many ways, the inclusion of the mass may become a supreme factor in the touch-down response of WTIVs onto the hard seabed and mainly depends on mass distribution of the WTIV components (such as leg, spudcan, hull) and the cargo.

To evaluate the influence of the WTIV mass on the dynamic touch-down of WTIV, the base mass of WTIV multiplied by 5 (note that such a large factor may not be a realistic representative of the engineering practice range; however, it was chosen to show the influence of the mass clearly). As was the case when the velocity was increased, the peak vertical forces as well as the penetrations increased with the increase in WTIV mass. However, it is observed that the duration of the impact is largely affected by increasing the mass of the WTIV. Again, it is observed that bedrock tend to remain in an elastic state during the impact (and minimal cracks or breakage) while with the conical leg geometry, the further penetration and local rock breakage noted. It was also observed that the rate of mobilization of the resistance force on the leg, regardless of the geometry, is not affected by increasing the mass of WTIV. The latter was not observed with the doubled impacting velocity. Horizontal forces up to 40MN were found in the case of the conical leg, although in the case of spudcan, the horizontal forces remain below 10MN. Again, the mobilization of large horizontal forces can be explained by the fixity of the leg tip in the rock mass.

EFFECT OF ROCK STRENGTH

The effect of the strength of the rock was assessed by reduction of the rock breaking strength up to 10% of its original value. The results are shown in Figure 10. As can be seen, the vertical forces acting on the WTIV legs decreased as substantial kinetic energy loss occurs due to the breakage and failure of the rock around the impact zone which resulted in larger penetrations even in the case of spudcan impact. In the case of spudcan case, 50% of the impacting kinetic energy was lost due to the local rock failure while 78% of the kinetic energy loss was observed for conical leg geometry.

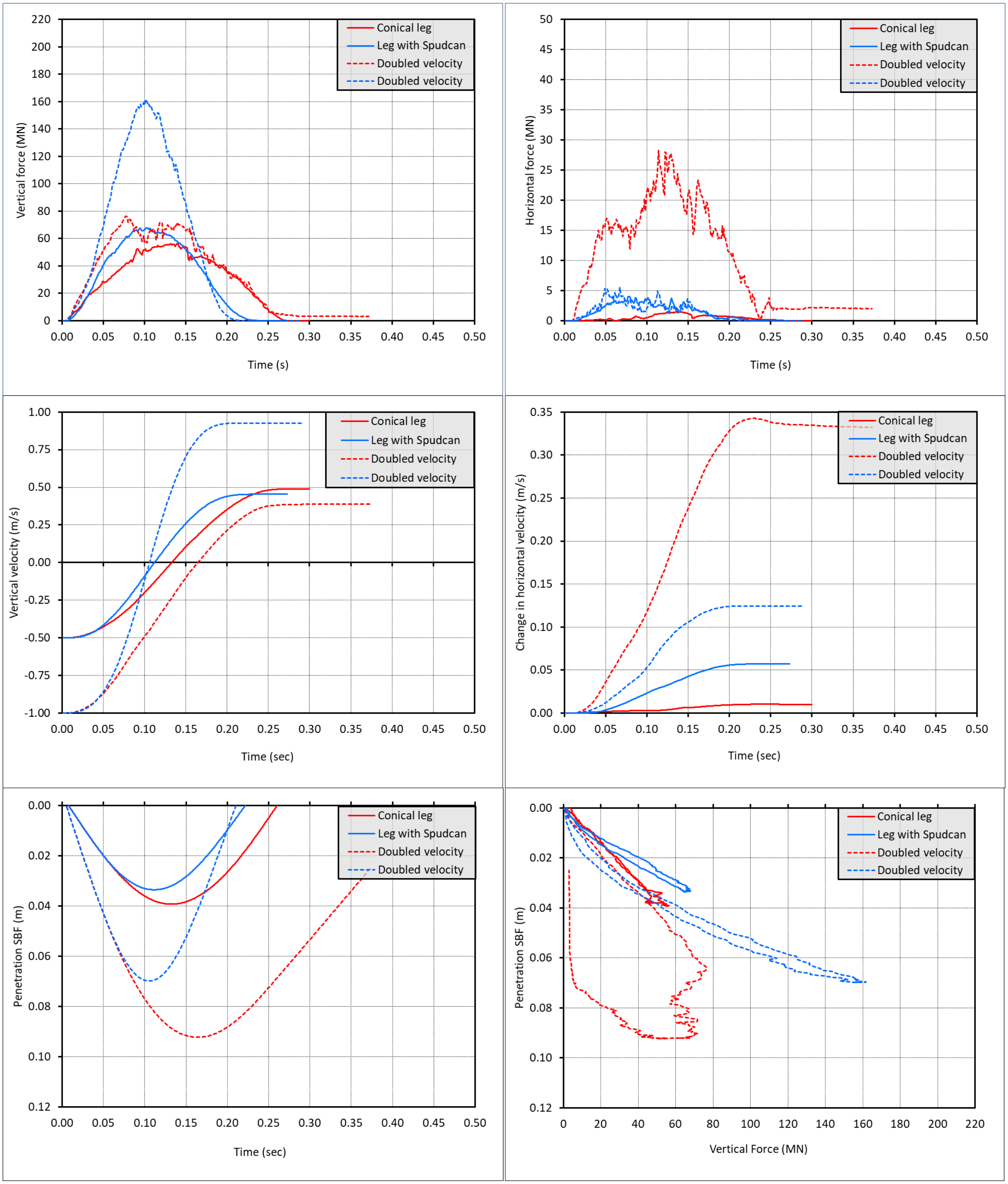

Figure 8: Effect of Impact Velocity

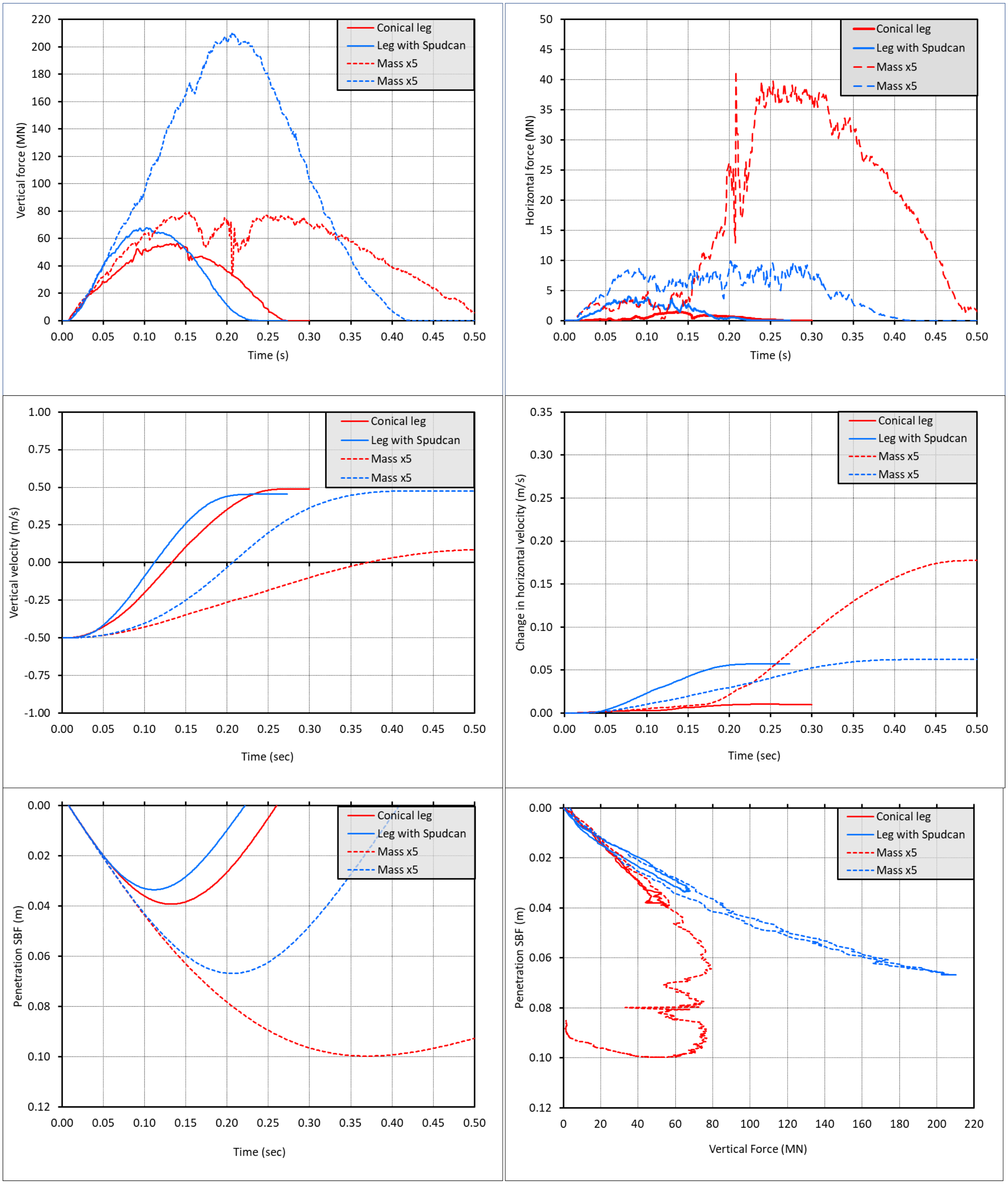

Figure 9: Effect of Mass

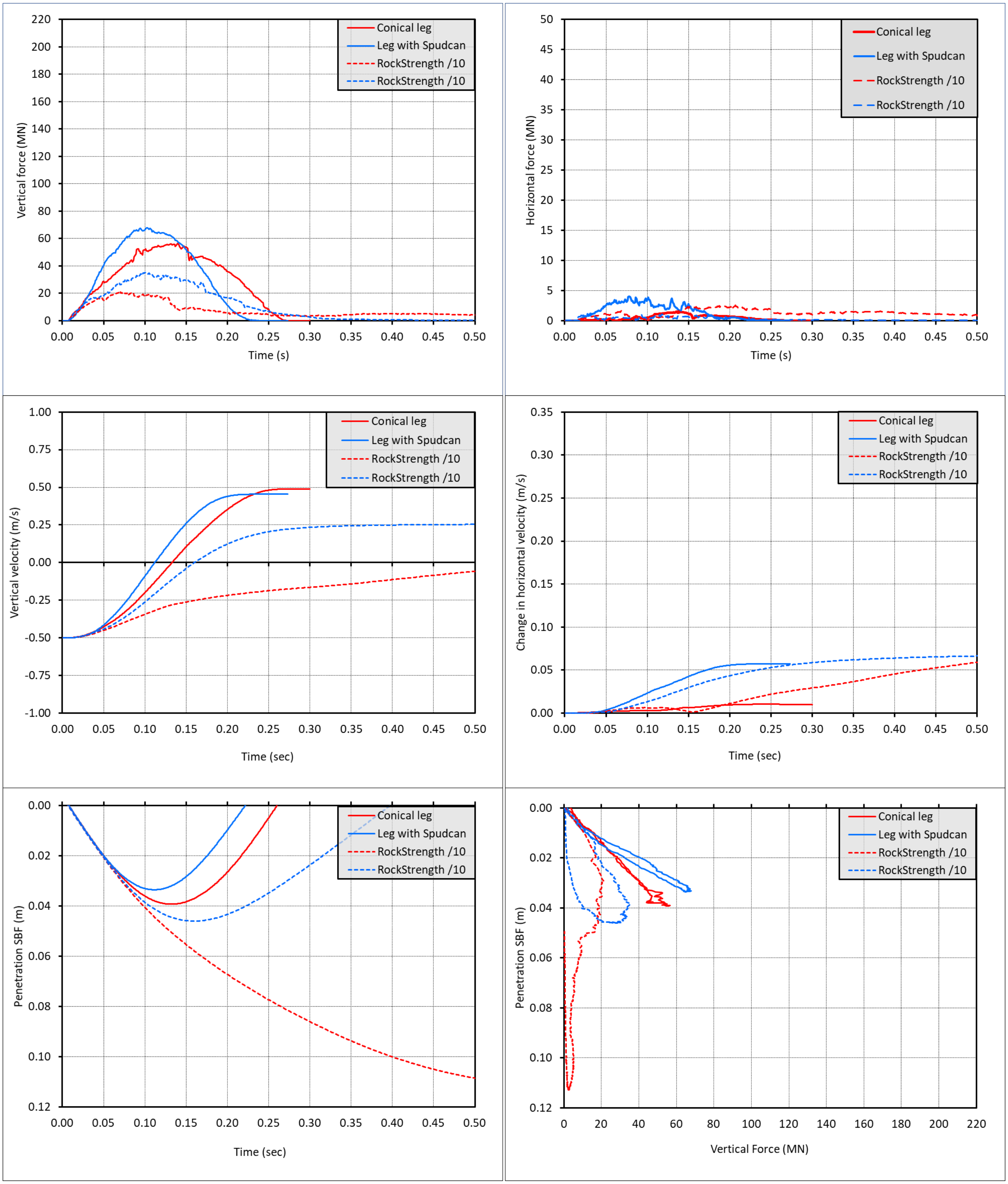

Figure 10: Effect of Rock Strength

SUMMARY AND CONCLUSIONS

This article attempted to demonstrate a full two-way dynamic impact solution for the touch-down of the WTIV units on the hard seabed by presenting an insight into the mechanics of the impact and performing a numerical-based parametric study to show the effect of impacting velocities, mass, geometry and the rock strength. Obviously, factors increasing the impact energy (e.g., increasing impacting velocities and mass) influence the mobilized loads acting on the leg tip. Figure 10 gives a good overview of the results both for conical leg and spudcan geometries when impacting velocity and WTIV mass are changed. This is only valid for the horizontal to vertical velocity ratio of 0.5, which was kept constant in this study. It is clearly shown that the magnitude of mobilized horizontal forces depends mainly on the leg tip geometry as well as the penetration depth, which leads to partial fixities.

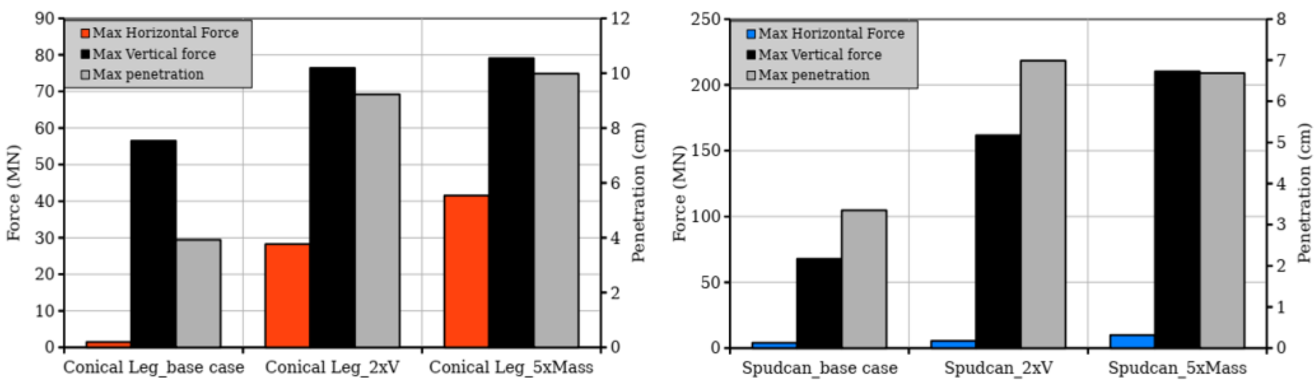

Figure 11: Overview of the maximum vertical/horizontal forces and leg tip penetrations for the 2 geometries considered.

At the operational level, offshore installation contractors adopt various approaches when jacking operations on the hard seabed is encountered: for instance, modifications on the shape of spudcans or legs, installation of damping elements on the bedrock and/or on the WTIV leg tips.

From the engineering perspective, it is of the utmost of importance to:

- determine the range of rock stiffnesses and strength by a thorough laboratory study. In addition, sufficient geophysical studies to be conducted to spot the joints (if any) within the rock mass
- conduct thorough hydrodynamic and motion analysis of the WTIV to deliver a range of possible impacting velocities of WTIV leg tip
- and to perform a full two-way dynamic impact analysis to determine the possible vertical and horizontal dynamic forces on the spudcan and to check those forces against the allowable forces as advised by the WTIV manufacturer

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