

Article

Review of Structural Strength in the Event of a One-Leg Punch through for a Wind Turbine Installation Vessel

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Abstract: As the demand for eco-friendly energy increases, the offshore wind power generation sector is showing rapid growth. As offshore wind turbines become larger, the need for specialized installation vessels is becoming a more crucial issue. Wind turbine installation vessels (WTIV) require a necessary pre-loading process where the legs and spudcans are penetrated into the seabed to secure stability during installation. Due to these operational characteristics, the installation work can be completed safely when safe pre-loading is finished. Analyzing previous structural collapse accidents investigated by HSE, 53% of them were punch-through problems related to the seabed, which occurred with a high frequency. Therefore, these lead to major accidents, which is a very high-risk problem. In this study, we investigated and analyzed the punch-through accident cases, and a WTIV model with six legs was applied to numerically examine the maximum vertical reaction force variation when punch through occurs for each leg. The maximum vertical reaction force takes place in leg number three when a punch through occurs in leg number five and maximum stress exceeds the allowable criteria in both hull and legs. This requires proper structural reinforcement such as an increase in the thickness and change in the high-yield stress. The key results of this investigation can be used to determine the basic specifications of wind turbine installation vessels, and the reaction force distribution pattern can be used as fundamental data for leg and hull structural design.



Citation: Park, J.-S.; Yi, M.-S. Review of Structural Strength in the Event of a One-Leg Punch through for a Wind Turbine Installation Vessel. *J. Mar. Sci. Eng.* **2023**, *11*, 1153. <https://doi.org/10.3390/jmse11061153>

Academic Editors: Dongran Song, Tianhui Fan, Qingan Li and Young Hoon Joo

Received: 15 May 2023

Revised: 28 May 2023

Accepted: 30 May 2023

Published: 31 May 2023



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Keywords: wind turbine installation vessel; pre-loading; punch through; soil; reaction force

1. Introduction

Due to global environmental issues such as global warming and fine dust, there has been a continuous increase in investment in eco-friendly and renewable energy sources worldwide. Among these, offshore wind power is the fastest growing sector, and the capacity of wind turbines is also increasing to over 12 MW. The demand for dedicated wind turbine installation vessels (WTIVs) to install these large turbines is also expected to continue to increase [1]. WTIVs have their own propulsion systems and can travel to the installation site where they anchor their legs to the seabed and use an electrically driven jacking system to lift the vessel to a position where it is not affected by waves, as shown in Figure 1. Typically, WTIVs are used exclusively for transportation, installation, and maintenance purposes in offshore wind power complexes, but they are also being designed and constructed to be used for installing and dismantling the substructures of wind turbines. The deck area and shape are important design factors for WTIVs. A wide deck has the advantage of increasing cargo capacity and providing ample space for faster work. However, increasing the exposed surface area to various environmental loads can result in increased structural loads and require a larger jacking system capacity due to the increased elevated weight. In particular, increased weight accelerates dynamic effects and has a significant impact on the design of legs and hulls.



Figure 1. Operating WTIV of Swire Blue Ocean. (<https://splash247.com/cadeler-firms-up-scottish-offshore-wind-turbine-installation-deal/deal/> accessed on 15 May 2023).

To carry out the installation of a WTIV, the spudcan should be penetrated into the seabed, and the final penetration depth depends on the supporting resistance of the seabed. As installation procedures can change, spudcan penetration work for fixation is required every time, and it is crucial to accurately assess the soil conditions that contain strong nonlinearity. However, since wind farms are extensive, the behavior of spudcan penetration is predicted by sampling major locations. In particular, in soil conditions consisting of sand and clay layers during pre-loading, punch-through phenomenon occurs rapidly in the clay layer after a relatively strong and stiff sand layer, leading to rotational moments on the structure and potential structural damage or capsizing of the vessel. Structural safety evaluation using analytical modeling is most important in order to manage the high risk caused by such punch through.

The purpose of this study is to conduct a structural safety review for the conditions in which the punch through of individual legs occurred using detailed FE analysis modeling. The legs were modeled using 1D beam elements, and 2D shell elements were applied to the other members including the hull. The jack case connection part responsible for load transmission connects the leg and the hull using a dummy beam. Throughout the screening analysis using Nastran solver, the fine meshing area where high stress occurs against the punch through of legs can be determined. The final analysis is performed using a detailed FE model. If the maximum stress generated exceeds the allowable stress, the process of reanalyzing is applied after confirming the structural reinforcement plan, as shown in Figure 2.

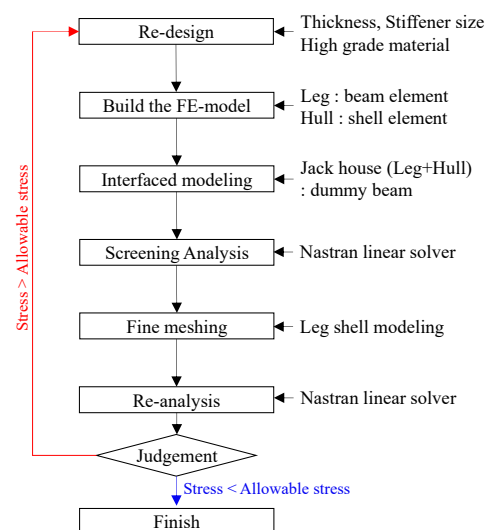


Figure 2. Analytical procedures of one leg punch through.

Therefore, it is essential for engineering to address this issue. The following summarizes the major previous studies on the mentioned problem.

Vladimir Rapoport et al. [2] developed a procedure for predicting ground settlement in real time during the pre-loading of jack-up rigs. They calculated and visualized the leg load and penetration depth in real time to the user. They suggested that by monitoring the significant increase in leg penetration depth and managing pre-loading accordingly, ground settlement can be prevented.

Vlahos et al. [3] performed experiments using a 1/250 scale model to conduct penetration tests of a spudcan on clay. The jack-up model was designed to measure shear and axial forces on the leg, as well as displacement and rotation angles of the soil and hull. Through the experiments, they observed the phenomenon of load redistribution at the corners of the spudcan and around the soil, as well as the behavior of the loss of rotational restraint of the spudcan due to the occurrence of the initial yielding of the soil.

Mahanta Rupam [4] compared the evaluation criteria provided by SNAME and ISO codes with the results of the MAHAJACK program developed in his study to assess ground settlement that occurred during the pre-loading process on the east coast of India. The data of the sea area where the accident occurred were taken from a geological survey report and consisted of clay and sand layers. The SNAME and ISO procedures showed ground settlement occurring at a pre-loading of 76.5 MN, while the evaluation criteria proposed by the author resulted in 47.5 MN, with a soil layer depth of 7 m. The subsequent behavior was the same as the results from the existing evaluation formulas and the proposed results. As predicted, the actual accident had the possibility of ground settlement occurring at a sand layer of 7 m, and the pre-loading prediction method provided useful results when using the “wish in-place” model recommended by SNAME and ISO.

Agaesen Ron et al. [5] proposed a simplified calculation method to analyze the resistance effect between a spudcan and soil, which is not described in the current SNAME (2008) and ISO (2012) guidelines. It is based on a geometric simplification of soil resistance and flow around the spudcan, and the calculation results were in good agreement with the centrifuge test results from previous studies. To analyze the disturbance effect due to contact between the spudcan and soil, it is necessary to determine the appropriate sensitivity variables, particularly in experimental studies on penetration behavior over time and soil strength degradation below the spudcan.

Yin Qishuai et al. [6] conducted 17 field experiments in Bohai bay to verify the penetration behavior of spudcans by punch through. Through the experiments, they proposed a new method to prevent ground subsidence. Pre-loading was carried out with minimal air gap, and an extra spudcan structure was installed to distribute the ground reaction force. Finally, the three legs were filled with water simultaneously, and the amount of ballast was adjusted to less than 900 tons in one process.

Tae-Min Cho et al. [7] performed a global in-place analysis for leg structure in the WTIV. The analysis parameters such as environmental and soil condition were induced by actual measurements at a west-south offshore wind farm in Korea. The author performed spudcan penetration analysis at the measured points, and it was confirmed that there was a possibility of punch through in most locations. In the study, the results were compared with the results of the simply supporting condition and soil stiffness by site specific measurement when reviewing the structural strength of the leg. The safety margin was 25%, based on the maximum strength in case of the imposed boundary condition. However, the case of considering actual stiffness increased significantly to 70%. It was suggested that this pattern was characteristic, and that it should be well considered from the perspective of structural optimization of the leg in the future.

Hu Pan et al. [8] conducted a study on theoretical evaluation criteria for accurately predicting the ground settlement phenomenon that mainly occurs when sand is located on top of a clay layer. This study compares the existing ISO and SNAME methods and, furthermore, compares the existing literature and the newly proposed theoretical model. One of the advantages was the development of a new structural model that can predict

the behavior after the maximum bearing capacity of the sand soil, which can be applied to a wide range of relative densities of sand. While the accuracy can be high for cases with similar characteristics to offshore soil considered in the study, there is uncertainty in the results for other types of soil properties. Previous studies have underestimated the effect of trapped soil beneath the spudcan, and the new evaluation method improves it to resemble the actual penetration process.

Tao Lyu et al. [9] established a reliability analysis model of jack-up against punch through, considering structural uncertainty. In order to identify the failure state, an improved reliability solution method was developed based on a sparse auto-encoder (SAE) deep learning network model. Sparse self-coding algorithm was used in the training of the deep network, and a Softmax regression model was established to solve the identification and classification problem of the output layer. The first application of the technique was the study of an HYSY 941 jack-up platform. More specifically, numerical calculations of structural ultimate bearing capacity was calculated, and the influence of model parameters on the prediction accuracy of the failure state was discussed. The results show that implicit performance function can be constructed accurately using the SAE-MC method by reflecting on the relationship between the different critical safety states and structural vulnerability. Compared with a traditional BP neural network, the deep learning network has a higher prediction accuracy to failure probability. The dynamic risk grade in the process of pre-load operation can be determined quantitatively using the reliability analysis method mentioned.

In this study, the ground settlement behavior that may occur during the pre-loading process of a six-legged WTIV and its effect on the structural strength of the legs and hull according to the pre-loading sequence are examined using numerical analysis methods. As monitoring systems are typically used during pre-loading operations of WTIVs, the ground settlement behavior was limited to occurring in only one leg.

2. Basic Methodology

In general, WTIV can install both sub-structures and wind turbines, but, depending on the shipping company's plan, they are being utilized to install only wind turbines. After loading the wind turbines on the deck using a crane at the port, it moves to the installation complex and, at this time, all legs have been extracted in an upward direction, as shown in Figure 3a. The WTIV arrives at the installation site, the legs are lowered to the seabed, and positioned as shown in Figure 3b,c. To install an offshore wind turbine, the hull is moved upward, where it is not affected by waves, as shown in Figure 3d. For safe pre-loading of WTIV, the spudcan is penetrated to a height that can withstand environmental load. At this time, the hull is raised and lowered while reducing the buoyancy to obtain the necessary load. Another advantage of the elevating of the hull is that it improves the structural safety of the WTIV by reducing the influence of the wave force, which is the main external load.

2.1. Punch-through Phenomenon

Since the main purpose of WTIV is to install offshore wind turbines, the most important pre-loading for the installation must be completed safely. To this end, it is necessary to be able to accurately predict the mutual relationship between spudcan and soil. The collapse behavior of representative soils has a fairly strong non-linearity, and measuring work requires enormous cost and time, which acts as a significant constraint. While pre-loading is in progress, the leg deformation data near the jack case must be carefully checked. The biggest reason for this is that there is a possibility of structural damage as the legs and hull tilt to one side according to the change in the characteristics of the seabed. Since the spudcan is fixed on the seabed, the damaged part is the leg, where it meets the lower part of the hull, and it can be schematized, as shown in Figure 4. Especially, the composition of a sand and clay soil layer rapidly changes the penetration movement because of the different soil stiffnesses. In general, sand is stiffer than clay. Punch through is likely to occur under these soil characteristics' conditions.

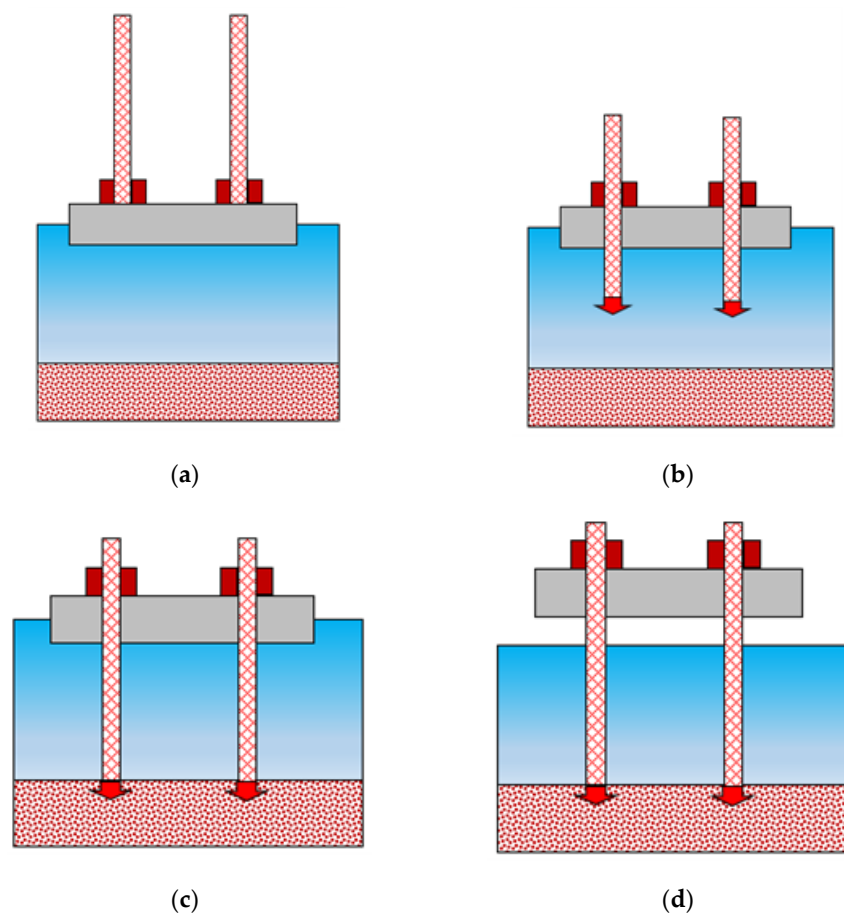


Figure 3. Several kinds of WTIV operating modes: (a) transit, (b) leg lowering, (c) pre-loading, (d) elevating.

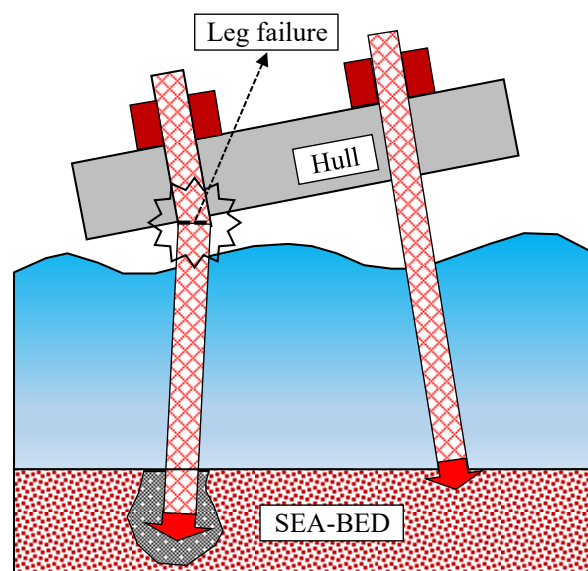


Figure 4. Example of structural damage of leg under punch through.

The above-mentioned structural failure is caused by the relationships between the soil and spudcan, so it is necessary to think about preventing them. The UK's International Organization for Workplace Health and Safety (Health and Safety Executive) [10] investigated accident cases of jack-up rigs that have been operated for decades and the results are presented in Figure 5.

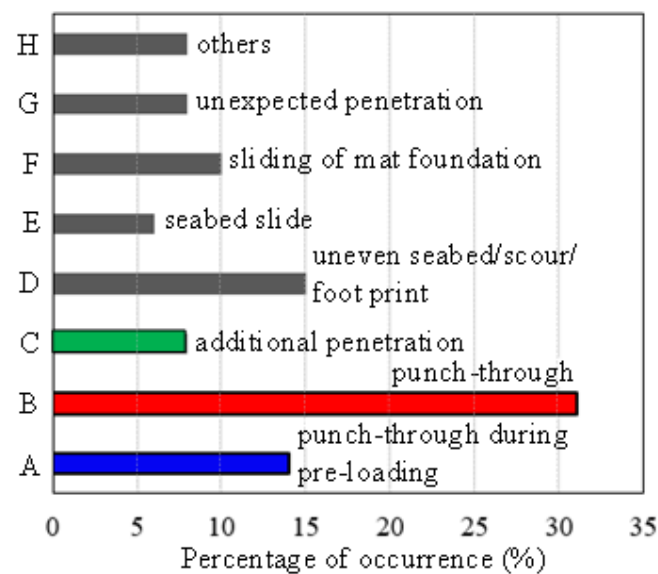


Figure 5. Percentage of the accidents according to the cause of failure (the data was from HSE 2004 [10]).

Accidents caused by punch through, including penetration problems, account for 53% of the total, indicating a fairly high accident frequency. Figure 5 shows an example of the calculated spudcan penetration behavior using the soil property values of the west– south sea wind farm hinterland (soil measurement report [11]). The sand layer is located from the surface to 8 m, while the clay layer extends to 25 m. The boundary between the sand and the clay layer is 8 m. In case of the pre-loading value exceeding 150,000 kN, soil collapse occurs up to 25 m due to the punch-through phenomenon, as shown in Figure 6. If any one of the WTIV legs is subjected to this situation, the structural collapse referred to in Figure 4 can be expected.

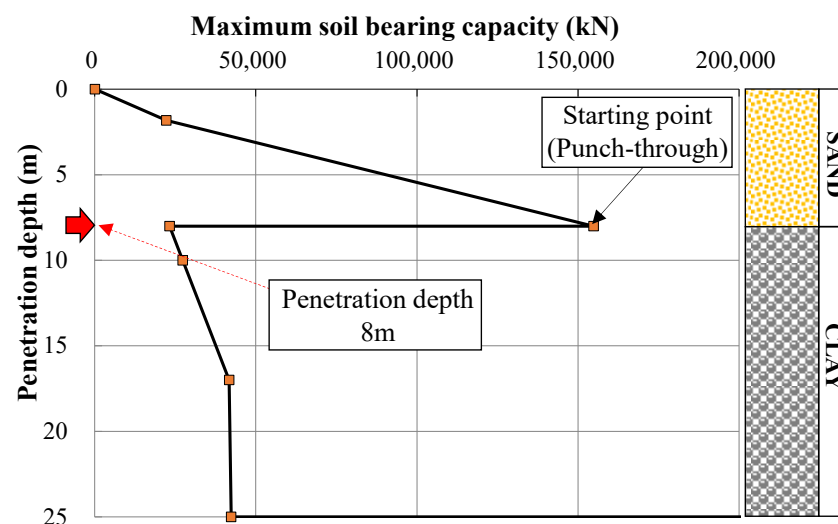


Figure 6. Example result of the soil penetration curve with clay over the sand layer.

2.2. Pre-Loading

The wind turbine installation vessel (WTIV) loads the nacelles, towers, and blades in separate spaces on the deck and moves them to the installation complex.

When arriving at the wind farm locations, legs are penetrated into the seabed for installation work, while the hull is brought to the surface of the water in a position that makes crane work easier. The seabed penetration process is pre-loading, since it uses its

own weight to penetrate; it involves controlling two or three legs simultaneously and iterating to the target penetration depth.

The number of legs in the plan view condition of the analysis model used for analysis is shown in Figure 7. Legs 1 and 2 are located in the direction of the bow, and leg 6 is where the stern crane is located. The pre-loading method uses three legs and controls 1–4–5 and operates 2–3–6 in turn. When using two legs, pre-loading is performed through combinations of 1–4, 3–6, and 2–5.

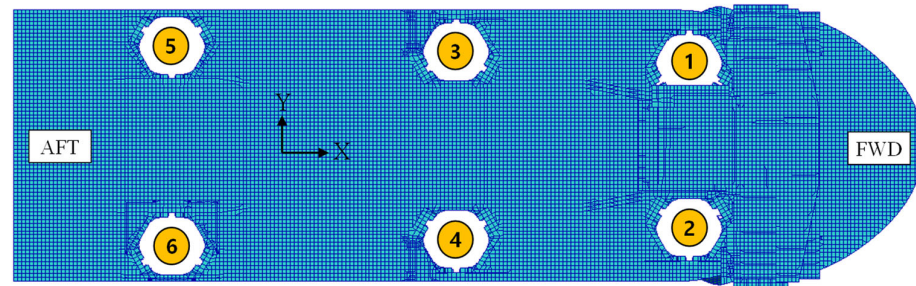


Figure 7. Leg-numbering definition.

3. Finite Element Analysis and Discussion

3.1. Finite Element Analysis Model

The structural analysis modeling was performed using MSC Patran/Nastran Version 2012 [12], a structural analysis program based on the finite element method. For the modeling of the plate member, a two-dimensional shell element was used, and a one-dimensional beam element represented as a stiffener. As for the size of the basic element, the width between one longitudinal stiffener (700 mm) was applied. The total number of elements used in modeling is 821,842 and the number of nodes is 738,479. The hull model view is shown in Figure 7a,b; it has six large penetrating structures in the hull.

The analysis model can be classified into three element sizes, as shown in Figure 8. The area of the interfaced joint between the hull bottom and leg has an element size of 30 mm, which considers the actual cross section of the rack and chord. The remaining leg part is 2000 mm using the beam element. The hull is modeled based on the average stiffener width of 700 mm, and the leg well is divided into elements with a size of 200 mm, as shown in Figure 8c. Three racks and chords are arranged in a vertical direction, as a shaped triangle leg, and a pipe called a brace is connected between them, as shown in Figure 8d.

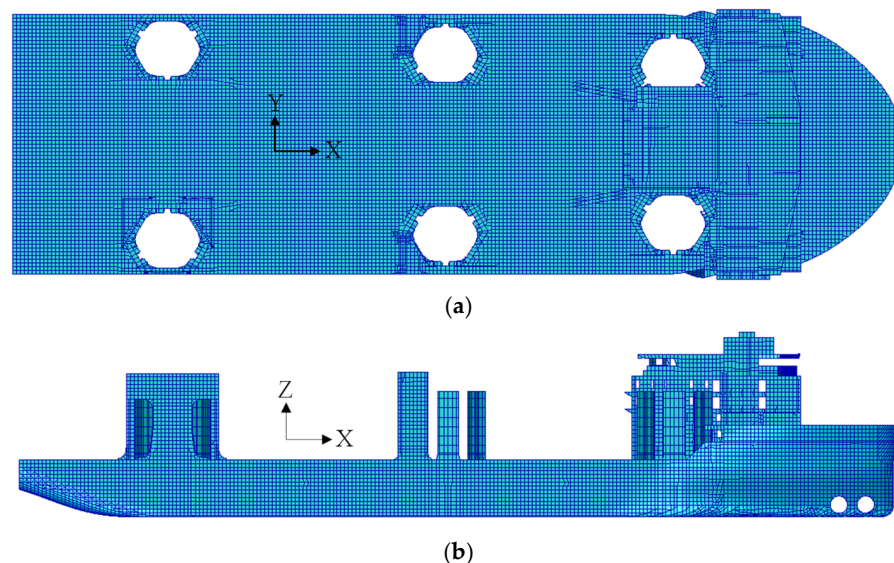


Figure 8. Cont.

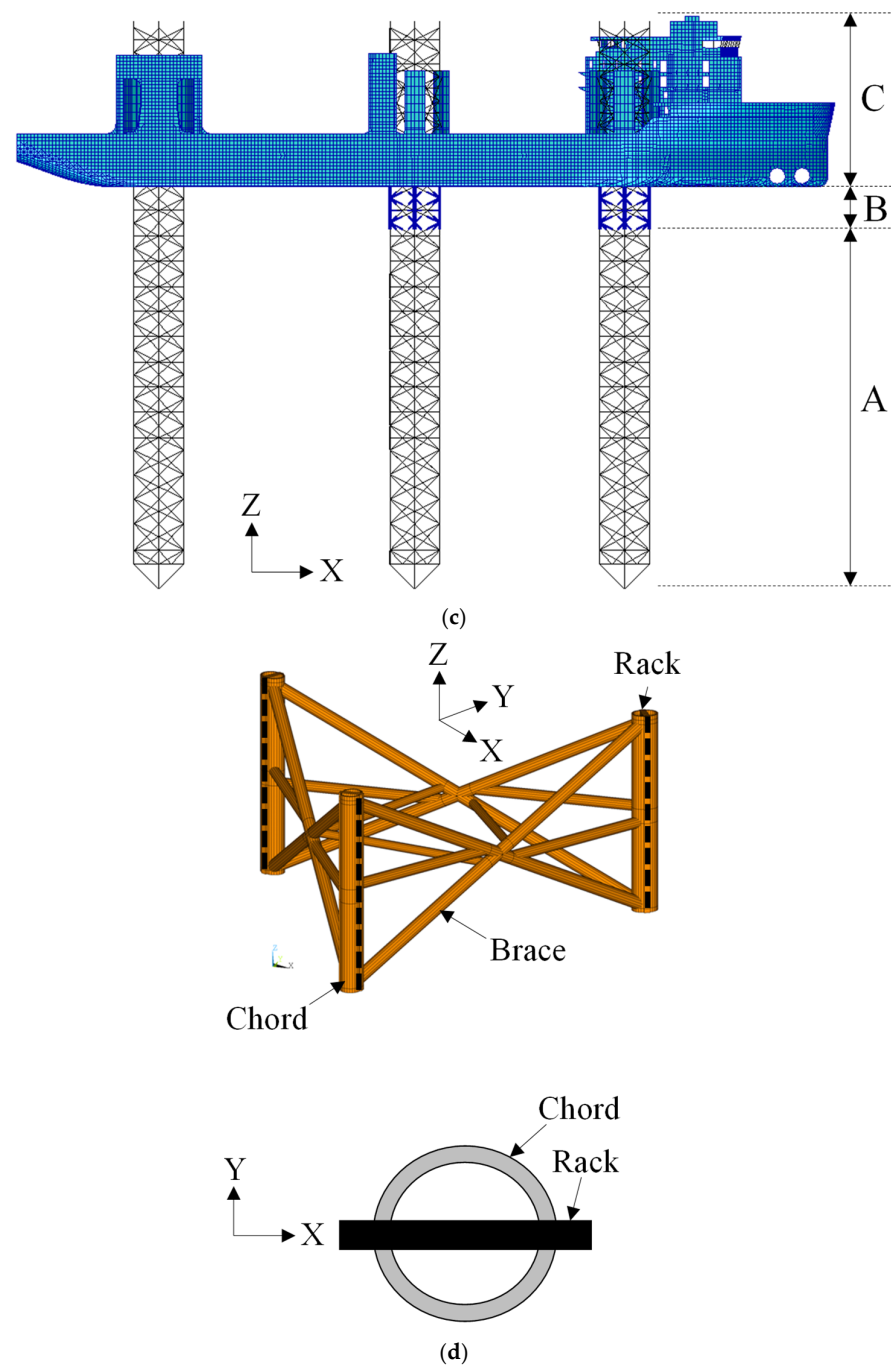


Figure 8. FE-model view: hull and whole WTIV (mesh size category: A: 2000 mm, B: 30 mm, C: 700 mm). (a) Plan view of hull, (b) elevation view of hull, (c) elevation view of whole model, (d) detailed leg model (rack, chord, and brace).

The WTIV has six legs, and the legs can move up and down through the area called the legwell. The main specifications of the installation vessel are provided in Table 1.

3.2. Finite Element Analysis Model

At the end of the leg where ground subsidence occurred, the displacement in the vertical direction (Z) was removed, and only the horizontal directions (X, Y) were fixed, which are summarized in Table 2. The reason for this is that the spudcan penetrates into the soil layer through pre-loading and, at this time, this is to realize the effect of supporting the soil.

Table 1. Main dimensions of the target WTIV structure.

Specification	Value
Length overall	161.0 m
Length between perpendiculars	155.6 m
Breadth overall	49.0 m
Depth, molded	10.4 m
Length of leg	105 m
Number of legs	6
Total hull weight	37,500 mt

Table 2. Leg boundary conditions according to sequence of punch through.

L.C.	Boundary Condition					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
1	Z-Free	Fix	Fix	Fix	Fix	Fix
2	Fix	Z-Free	Fix	Fix	Fix	Fix
3	Fix	Fix	Z-Free	Fix	Fix	Fix
4	Fix	Fix	Fix	Z-Free	Fix	Fix
5	Fix	Fix	Fix	Fix	Z-Free	Fix
6	Fix	Fix	Fix	Fix	Fix	Z-Free

Note: Z-free is constrained X and Y directional displacement; fix is constrained X, Y, and Z displacement.

3.3. Change in Leg Reaction Force

Table 3 summarizes the vertical reaction force distribution results whenever the leg where the punch through occurs changes. However, the total reaction force is the same as the maximum elevating weight of 256,270.3 kN. Due to the nature of the WTIV, the center part, which has the widest deck-loading area, supports a large load, and the deckhouse, a crew living structure, is located in legs 1 and 2 in the fore-end part. Leg number 6 at the aft end is characterized by the location of a main crane used to install and dismantle wind turbines. Depending on the leg location where punch through occurs, the position of the maximum vertical reaction force also changes in various patterns. The largest reaction force appears in leg number 5 when punch through occurs in leg number 3. The reason why the elevating load is the same, but the supporting point is no longer in condition, is according to the punch through of middle leg number 3.

Table 3. Results of the vertical reaction force according to sequence of punch through.

L.C.	Reaction Force for Z Direction (kN)					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
1	-	71,855.3	76,354.0	37,209.5	46,541.3	24,310.2
2	71,470.9	-	37,086.0	77,163.8	25,477.5	45,072.0
3	65,997.4	42,519.6	-	46,948.5	62,791.0	38,013.8
4	41,421.5	67,048.3	47,044.7	-	39,559.9	61,195.9
5	48,528.4	21,326.1	84,238.0	33,180.2	-	68,997.6
6	20,940.4	49,547.3	33,695.6	82,556.3	69,530.7	-

Figure 9 shows the reaction force results under one leg punch through load conditions 1, 5, and 6. The maximum load is shared in leg numbers 2 and 3 adjacent in the longitudinal

direction when punch through occurs in leg number 1, as shown in Figure 9a. The maximum reaction force is concentrated at leg number 3 to the center location when punch through occurs in leg number 5. Among the load conditions, it is a characteristic that the change in reaction force is the biggest, as shown in Figure 9b. In case of punch through at leg number 6, where the main crane is located, the load-sharing effect is greater than load condition 5, as shown in Figure 9c. This difference is induced by asymmetric weight distribution according to the main crane arrangement.

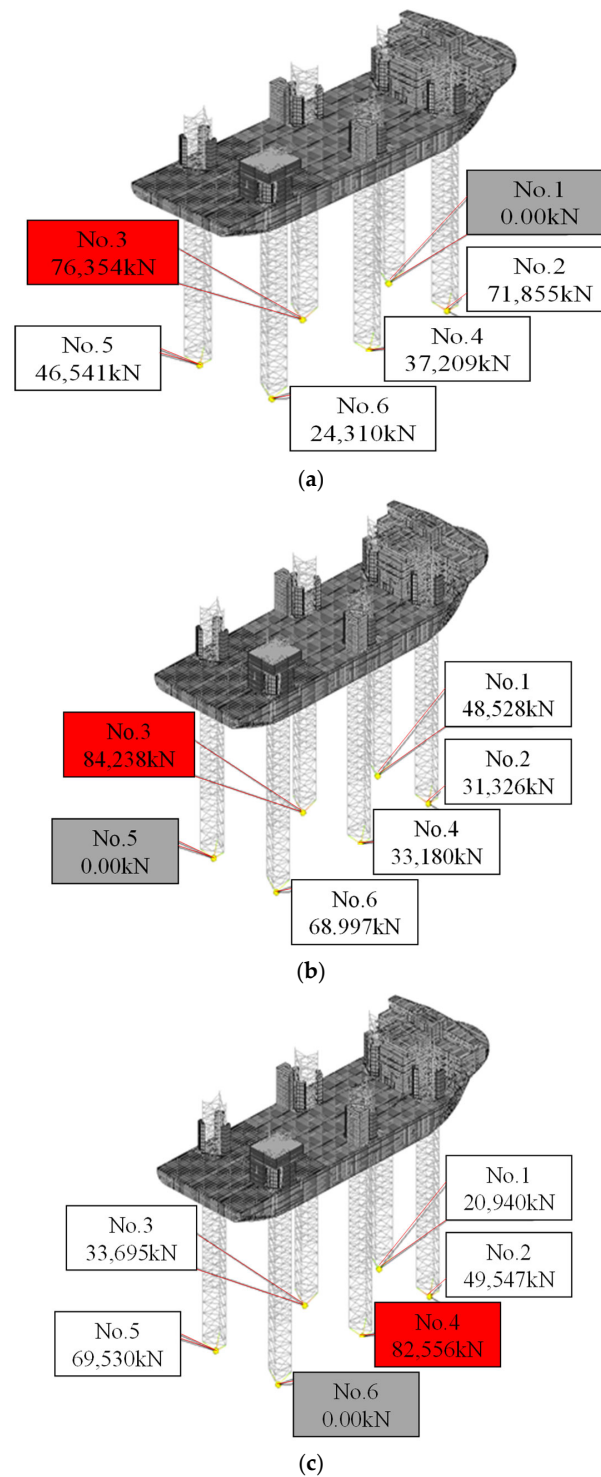


Figure 9. Reaction force distribution of the leg according to punch-through cases: (a) punch through at leg number 1, (b) punch through at leg number 5, (c) punch through at leg number 6.

The structural strength check of the leg was numerically reviewed according to the sequence punch through of the legs, and Table 4 shows that the allowable stress was not satisfied in the combination of axial stress and bending stress in conditions 1, 2, 5, and 6.

Table 4. Results of the reaction force according to sequence of punch through.

Load Condition	Comparison of the Maximum Stress for Leg (MPa)	
	Max.Von Mises Stress	Allowable Stress
1	562.0	
2	572.9	
3	458.3	552 ⁽¹⁾
4	463.8	363 ⁽²⁾
5	712.0	627 ⁽³⁾
6	635.5	

Note: ⁽¹⁾ is calculated by the following equation. Yield stress (690 MPa)/safety factor (1.25), ⁽²⁾ is yield stress (690 MPa)/safety factor (1.90), and ⁽³⁾ is obtained by yield stress (690 MPa)/safety factor (1.1).

The position of maximum stress is a vertical member where the leg meets the bottom of the hull where the maximum bending moment occurs. The end of the leg is fixed in the seabed, and it can be continuously moved as a cantilevered shape against environmental load. This phenomenon inevitably takes place at the maximum bending moment at the connection between the leg and hull bottom, where hull rigidity is greater than leg structure.

The allowable stress criterion used the guideline proposed by the Norwegian classification society (DNV [13]). The maximum stress is experienced at leg number 3, which is the vertical column member in Figure 10. As for the reinforcement, the thickness of the vertical column member should be increased from 80 mm to 92 mm, and the applicable section is two bays and should be applied to the 9.4 m section.

The maximum vertical reaction force is largely shared by the adjacent leg 3, and this tendency is the same as the result of the maximum vertical reaction force in leg 4 when the punch through occurs in leg number 6.

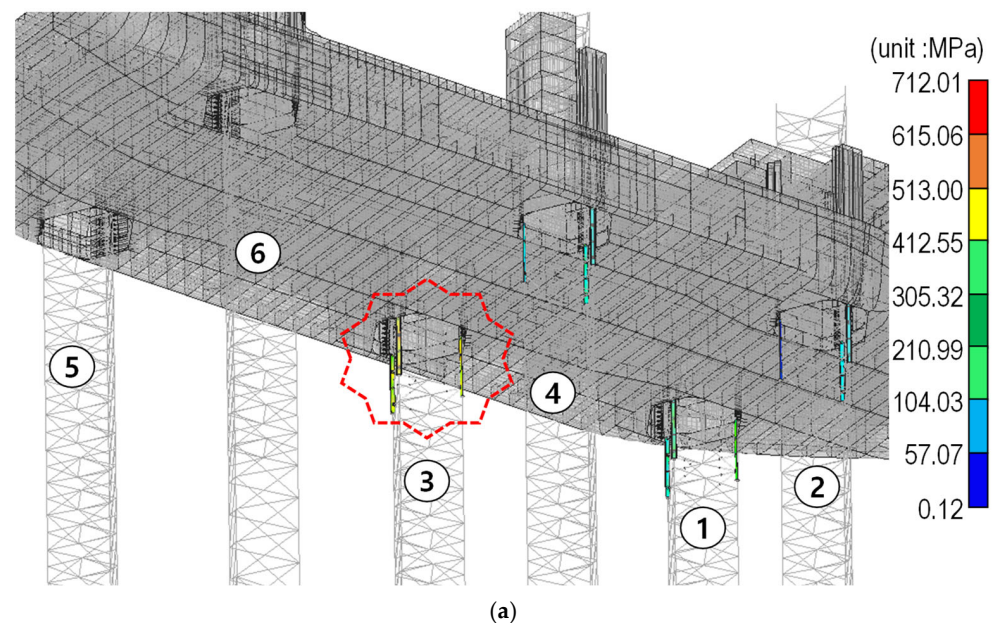


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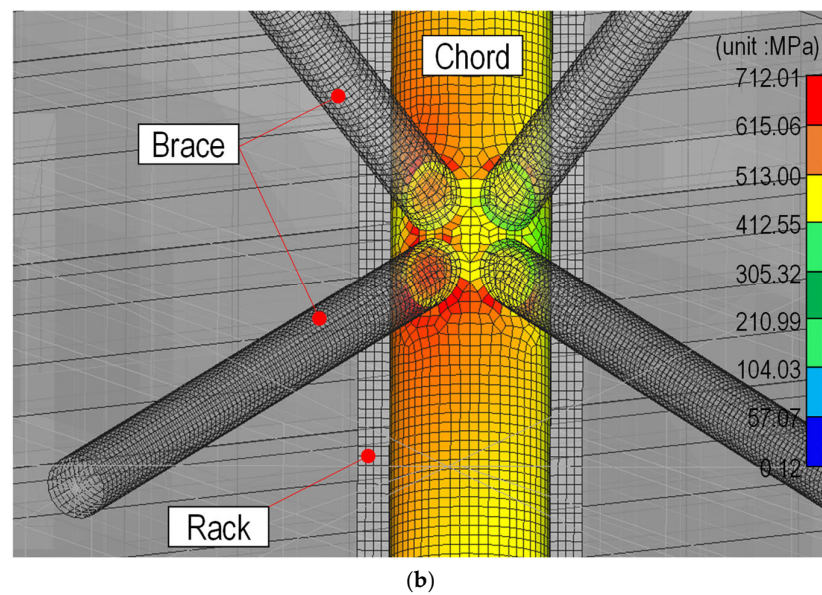


Figure 10. Maximum stress plot of the leg under punch through at leg number 5: (a) maximum beam stress (axial + bending), (b) maximum beam stress (detailed view).

Figure 11 shows the von Mises stress where the maximum stress occurs in the hull structure when punch through occurs in leg number 5. The maximum stress of 421 MPa occurs at the connection point of the leg and the adjacent hull bottom, which is greater than the allowable stress of 301 MPa. Therefore, this means that proper reinforcement is required, for example, thickness increase as well as a change in the high-grade material. As a detailed reinforcement method, it is desirable to replace the material with high tensile strength steel having a yield strength of 500 MPa. In order to reinforce the plate thickness, it is necessary to change the current thickness from 40 mm to 56 mm, but it is not easy to apply due to weld ability problems caused by the difference in thickness from the surrounding plate members.

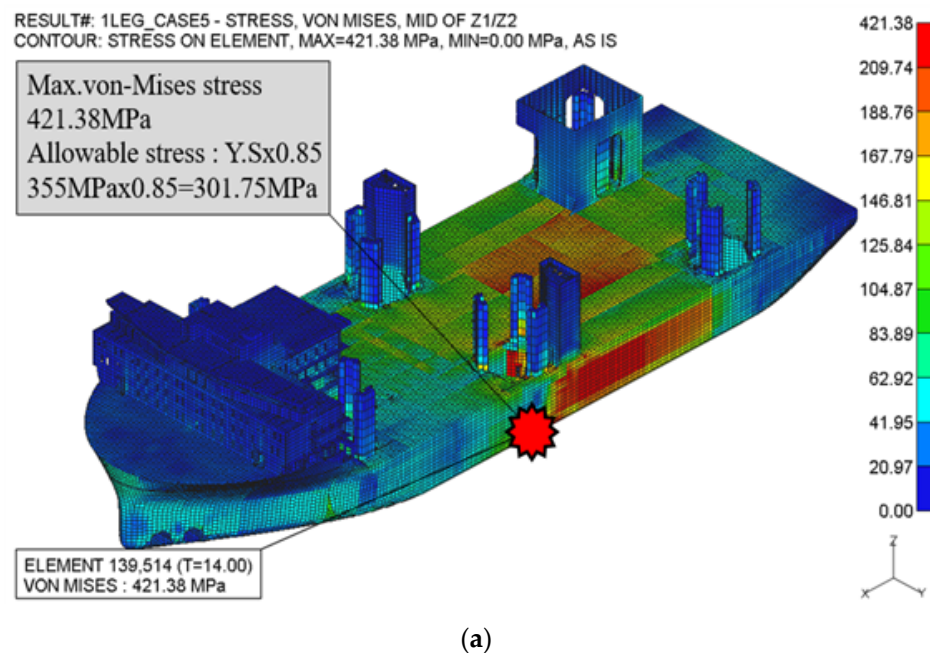


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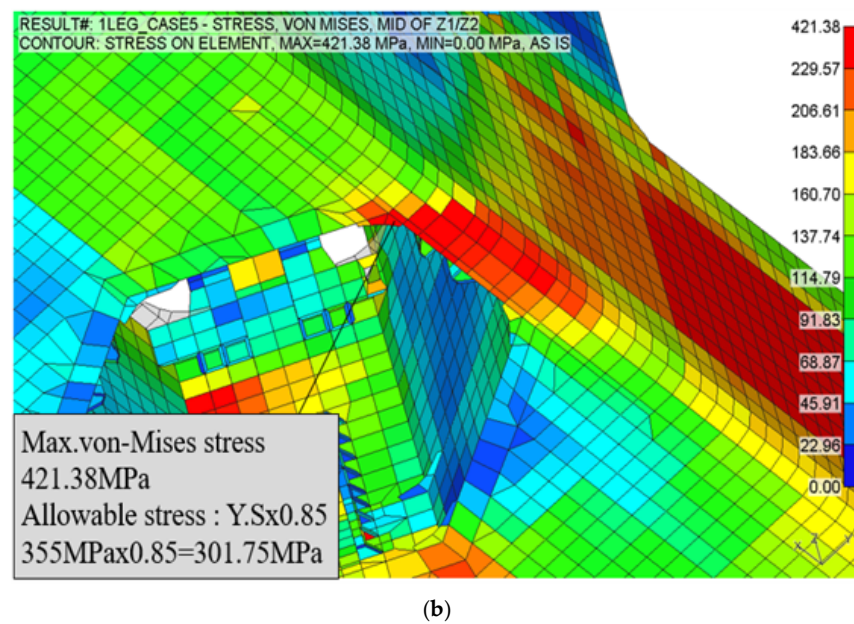


Figure 11. The von Mises stress contour under punch through occurs in leg number 5: (a) von Mises stress, (b) maximum von Mises stress (detail view).

Figure 12 shows the deformed shape of the hull according to punch-through conditions. The hull structure has a large displacement in the vertical deflection as rotational moment occurs at the leg induced by punch through. A large rotational displacement occurs at the wheel-house corner, resulting in a maximum of 398 mm, as shown in Figure 12a. The location and magnitude of displacement are almost similar as a comparison between condition number 1–2 and 3–4. The maximum displacement occurs at the aft end of 591 mm under load condition 5. Due to the punch through of leg number 3 located in the center, deformation occurs as the stern part is bent downward and the bow part is bent upward.

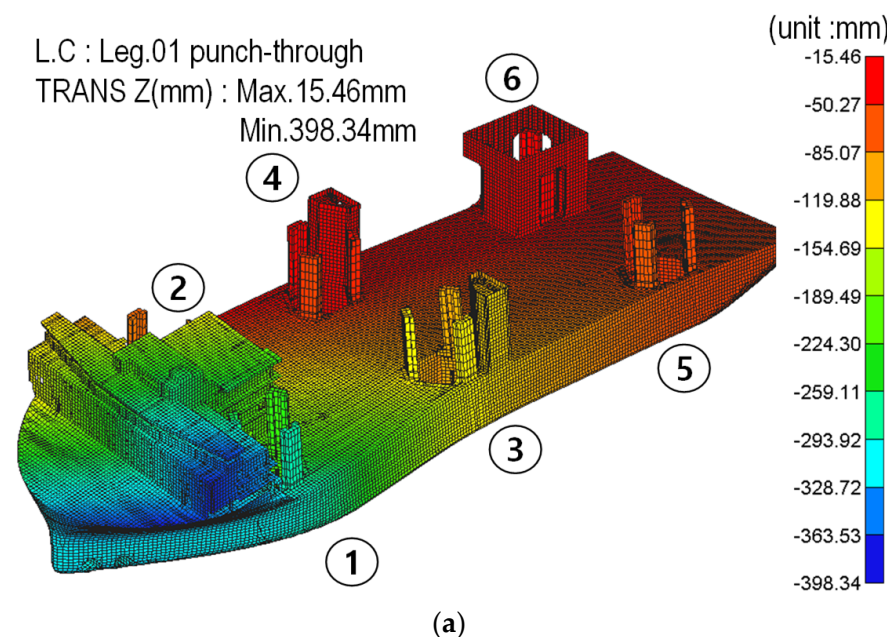
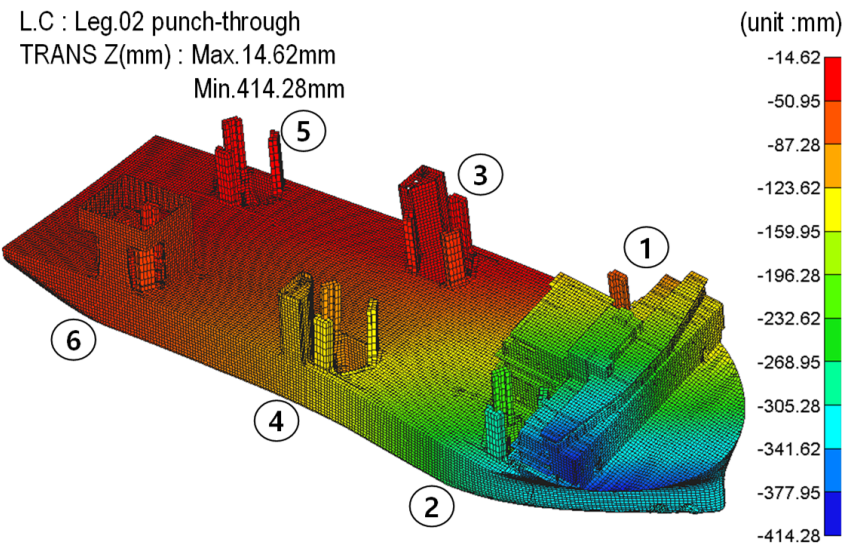
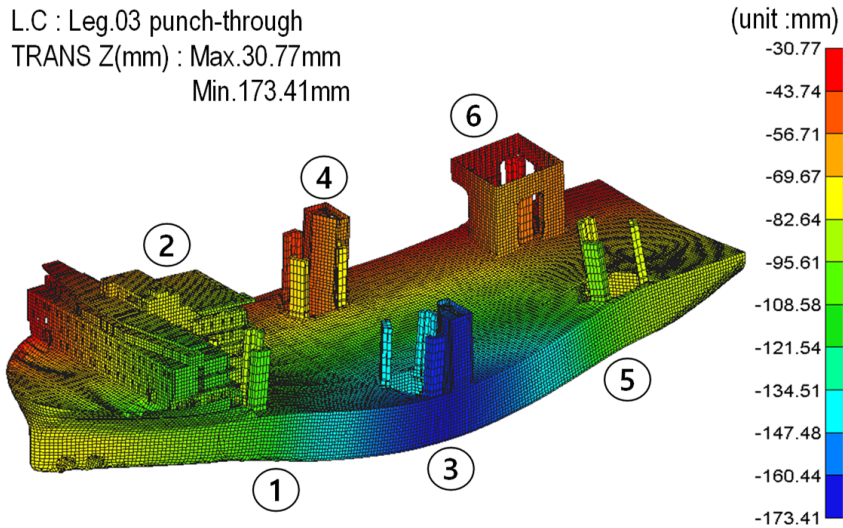


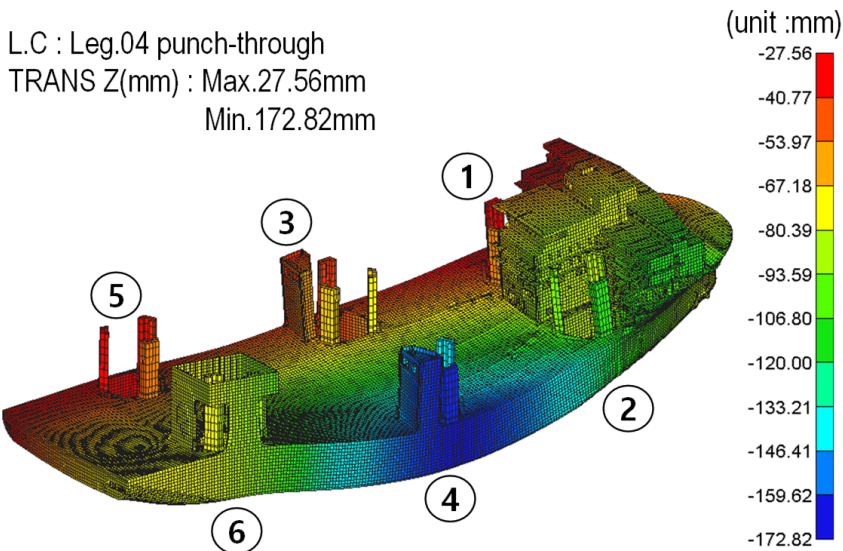
Figure 12. Cont.



(b)



(c)



(d)

Figure 12. Cont.

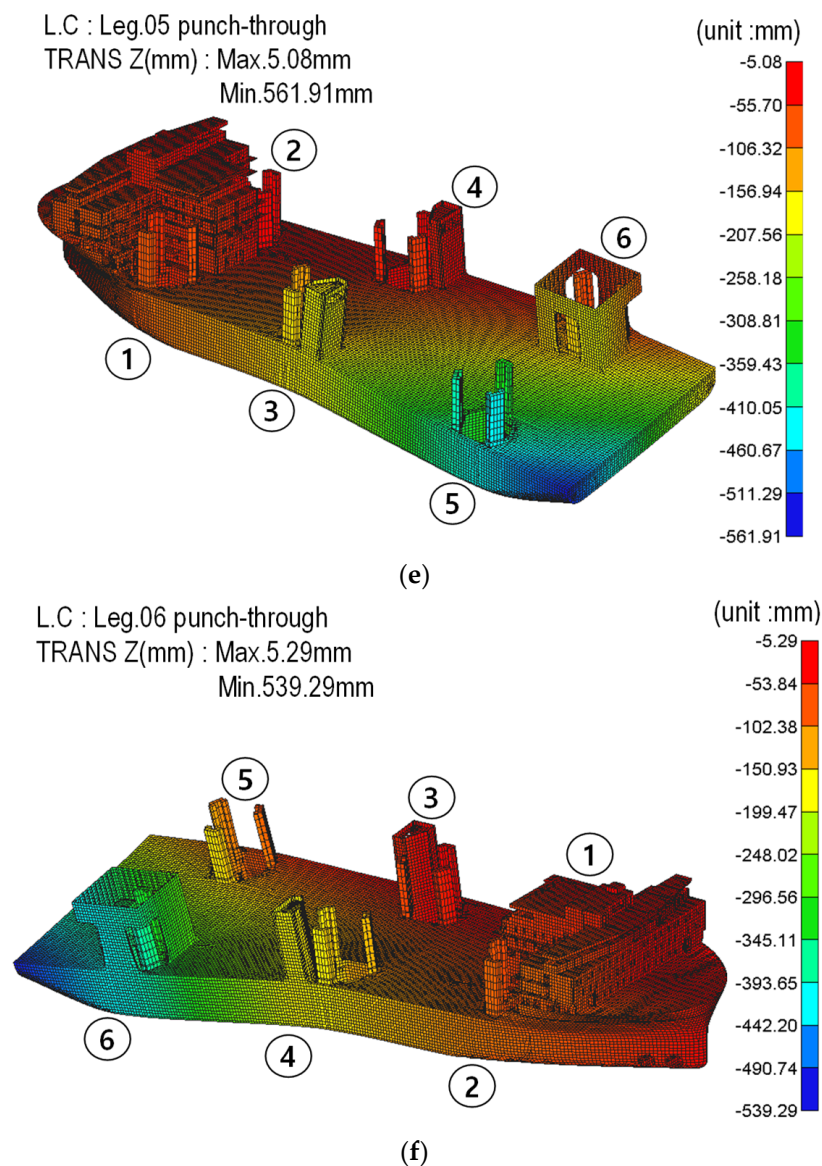


Figure 12. Maximum displacement and deformed shape according to sequence of punch through: (a) punch through at leg number 1, (b) punch through at leg number 2, (c) punch through at leg number 3, (d) punch through at leg number 4, (e) punch through at leg number 5, (f) punch through at leg number 6.

4. Conclusions Remarks

In this study, the punch through was the main point which was an essential process during operating WTIV. In order to accurately understand the phenomenon, structural analysis based on analytical modeling was performed. The cases of damage caused by punch through were investigated through the literature (HSE [10]) and accounted for approximately 53%, so the justification for risk management was confirmed. The WTIV model was a large size with six legs, and it was assumed that punch through occurs independently in one leg during installation. The conclusions obtained through the review are as follows:

- (1) Punch through is most likely to occur when the soil conditions consist of sand and clay layers. Once the results of these soil measurements are confirmed, a separate penetration behavior analysis should be performed to manage the risk.
- (2) Among the load conditions reviewed in the analysis, the maximum reaction force in the punch through at leg number 5 was 84,238 kN from leg number 3. This is because

the rotation of the hull occurs in the opposite direction. At this time, it is necessary to change the thickness and steel of the legs and part of the hull.

- (3) The maximum displacement of the hull is 561 mm provided by punch through at leg number 5 and it is caused by the free-end behavior at the tip of the stern.
- (4) Due to the nature function of the WTIV, the variable load is concentrated in the deck center. When punch through occurs in the bow and stern legs, the load distribution in the center leg increases. In order to reflect these characteristics, it is possible to operate more safely if the structure of the central leg is reinforced.
- (5) The large installation vessel used in the study has six legs and, compared with the case with four legs, the deformation of the hull is expected to be small because the distance is short. When developing future models, the number of legs and the distance are also variables that should be fully considered.

In reality, it is a very difficult task to create a structural design for legs against punch through. However, if the following matters are carefully observed, the WTIV can be operated more safely:

- A real-time monitoring system is installed and rack phase difference (RPD) is measured from the legs at the top of the jack case. Before the measurement of RPD, acceptance criteria should be established.
- If the allowable RPD value is exceeded, it is necessary to determine whether to stop pre-loading and proceed. The possible solutions are to divide the pre-loading step into smaller loads and change the installation location.

As a future study, a simple evaluating program should be developed that can calculate the maximum stress according to punch-through scenarios. This is to idealize primary structural members using the beam element to find the critical location and can be used to find the worst locations. Through this activity, it is possible to review various load conditions of the WTIV.

Author Contributions: Conceptualization, J.-S.P.; methodology, J.-S.P. and M.-S.Y.; data curation, M.-S.Y.; writing—original draft preparation, J.-S.P.; writing—review and editing, M.-S.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by “Regional Innovation Strategy (RIS)” through the National Research Foundation of Korea (NRF) founded by the Ministry of Education (MOE) (2021RIS-003).

Data Availability Statement: The data are not publicly available. The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Park, J.S.; Ha, Y.C.; Seo, J.K. A Study on Load-Carrying Capacity Design Criteria of Jack-Up Rigs under Environmental Loading Conditions. *J. Korean Soc. Mar. Environ. Saf.* **2020**, *26*, 103–113. [\[CrossRef\]](#)
2. Rapoport, V.; Devoy, S.D.; Alford, J.; Benbow, M.S.; Huthnance, W.B. Soil-Structure Interaction during Preloading of Jackup MODU's in Different Soil Conditions. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 1994; pp. 203–207.
3. Vlahos, G.; Martin, C.M.; Cassidy, M.J. Experimental Investigation of a Model Jack-Up Unit on Clay. In Proceedings of the Proceedings of the Eleventh ISOPE Conference, Stavanger, Norway, 17–22 June 2001; pp. 17–22.
4. Cho, T.-M.; Park, J.-S.; Ha, Y.-S.; Kim, B.-J.; Jang, K.-B. Global In-Place Analysis of WTIV Leg for Korean West-South Offshore Wind Zone. *J. Ocean Wind. Energy* **2015**, *2*, 121–127. [\[CrossRef\]](#)
5. Mahanta, R. Punch-Through Analysis of Jack-Up Rig at a Site Off the East Coast of India—A Case Study. In Proceedings of the Indian Geotechnical Conference IGC 2016, Chennai, India, 15–17 December 2016; pp. 1–4.
6. Aagesen, R.; Dean, E.T.R.; Lee, F.H.; Li, Y.P. Simplified Analysis of Chord and Brace Effects on Jackup Leg Penetration for Preloading in Soft Clay. *Can. Geotech. J.* **2018**, *55*, 1900–1907. [\[CrossRef\]](#)
7. Yin, Q.; Yang, J.; Xu, G.; Xie, R.; Tyagi, M.; Li, L.; Zhou, X.; Hu, N.; Fu, C.; Pang, D.; et al. Field experimental investigation of punch-through for different operational conditions during the jack-up rig spudcan penetration in sand overlying clay. *J. Pet. Sci. Eng.* **2020**, *195*, 107823. [\[CrossRef\]](#)

8. Hu, P.; Xiao, Z.; Leo, C.; Liyanapathirana, S. Advances in the prediction of spudcan punch-through in double-layered soils. *Mar. Struct.* **2021**, *79*, 103038. [[CrossRef](#)]
9. Tao, L.; Xu, C.; Chen, G.; Zhao, Y.; Li, Q.; Zhao, T. Reliability of Jack-Up against Punch-Through Using Failure State Intelligent Recognition Technique. *KSCE J. Civ. Eng.* **2019**, *23*, 1271–1282.
10. Health and Safety Executive (HSE). HSE Research Report 289, Chapter 3—Available Information. In *Guidelines for Jack-Up Rigs with Particular Reference to Foundation Integrity*; Health and Safety Executive: Bootle, UK, 2004.
11. Project, No.20123010020090 3-7. Soil Measurement Report. Optimized Leg Design and Development of Jack-Up System for Wind Turbine Installation Vessel (WTIV). 2013; 23–69.
12. MSC Software. Chapter 6; Material Modeling. In *Patran 2012 User's Guide*; MSC: Newport Beach, CA, USA, 2012; pp. 125–136.
13. Det Norske Veritas (DNV). DNV-RP-C104, SELF-ELEVATING UNITS, Chapter 6 Structural strength (ULS). In *Recommended Practice*; DNV: Oslo, Norway, 2011; pp. 46–53.

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