Title: Re-use of Furnace Foundations on Shell Moerdijk Plant (NL)

Process to accommodate extra loads on the piled foundation plate

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ABSTRACT

In early 1970s, Shell built 16 industrial furnaces for the Shell Moerdijk Chemicals Plant. Each pair of furnaces included 60 m high steel structures, based on a 14 x 16 m2 concrete plate with a 4.5 x 14.5 m2 "outrigger." The foundation plate is supported by 50-piece 380x380 mm2 precast concrete piles.

In the Shell Skyline Project, Shell renews 8 of these 16 furnaces, by re-using the furnace foundations. For the cracking furnaces, the upper part (convection section and steel structure) of the existing furnaces will be removed and replaced with a larger, heavier and higher convection section and steel structure. For the rejuvenated furnace not to exceed weight, a limit was set at 960T for a furnace pair.

Over the past 6 years, a wide variety of partners worked closely together in order to serve the Skyline project with the correct input to accommodate the new Skyline module structure on the existing foundations and make the project successful.

Therefore, extensive studies and investigations, as well as geotechnical and other various calculations, have been undertaken to accommodate the new furnace modules on the existing furnace foundations. These studies were mainly focused on:

1. Integrity status of foundation
2. Increase of the bearing capacity of the foundation, linear and non-linear
3. Rigorous weight control in all phases of the project

Keywords: Shell, re-use, project, multi-disciplinary, foundation, investigation, weight control

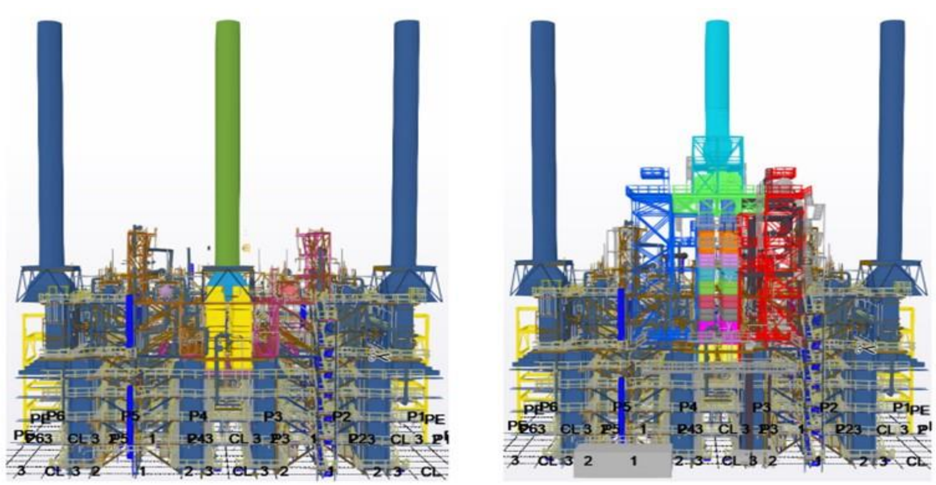

Fig. 1. Side view old situation (L) and new situation (R)

INTRODUCTION

Initiation of Project: Skyline – 16-year-old cracker furnaces replaced by eight modern furnaces

Sixteen Ultra Selective Cracking (USC) furnaces at the Shell Moerdijk Chemicals park were built in the 1960s (operational since 1972) and are reaching end of life. In 2017, a project was initiated to upgrade / replace these existing cracking furnaces. Since replacement was required, the opportunity arose to replace the existing furnace with a new, more energy efficient design. The new design will only require the rebuild of eight furnaces instead of the original 16 furnaces. The major advantage of the new design is an improved energy efficiency that will lead to a significant emission reduction. After completion of the Skyline project, the total CO_2 emission of the Shell Moerdijk Chemicals Park will be reduced by 10%.

Fig. 2. Bird eye perspective of Skyline project scope

Eight (F5-F12) of the 16 existing USC furnaces, which were built in the late 1960s and taken in service in 1972, were selected to be revamped to a larger capacity, by reusing the lower part consisting of the existing firebox and the existing foundation. The re-use solution option 3 was the cheapest compared to the two other options which were:

- Option 1; New furnaces on new location (30-40% more expensive vs option 3)
- Option 2; New furnaces on existing location (30-40% more expensive vs option 3)

The other remaining 8 USC furnaces will be taken out of operation once the revamp is done. The height of the convection section will increase by about 15 m. A new stack shared by two adjacent furnaces will replace the existing. The elevation of the stack exit will remain the same as current. The revamped furnaces will all have the same configuration, are capable of processing a variety of feeds and fit on the existing foundations.

The overall Skyline project entails a much larger scope as the furnaces are part the Inside Battery limit (ISBL). The Outside Battery Limit scope is left out of this keynote as it is not deemed relevant.

In this keynote the process and actions related to the foundation assessment will make use of the steps used within Shell for projects: Assess, Select, Define and Execute.

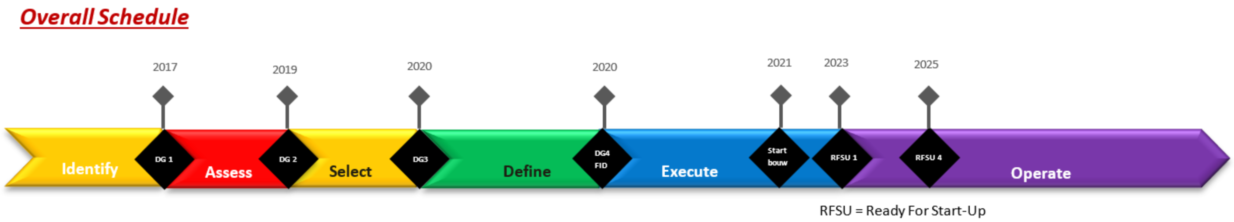

Fig. 3. Overall project schedule

Assess and select phase (2017-2019): feasibility of project premises by foundation verification

The project started in 2017 with a feasibility study, which covered a variety of options ranging from stick build to modular design for the complete furnace structures. Along with the options for the construction feasibility, it became more apparent that a complete demolition of a full set of two furnaces was not be feasible from both an economic as well as from a construction point of view. Removing the lower furnace part and potential foundations had a major impact on the whole project schedule and its economics. This would mean the project premises of another 20 years of safe, reliable and profitable operations could not be met. The choice was made to continue with a modular design for new convection parts and re-use of its foundations and furnace.

The civil department performed a desktop study in the select phase by examining the available documentation from the Moerdijk archives including drawings, calculations and existing data of the geotechnical situation. The data of pile driving records, and the exact length and pile penetration and other structural info, could not be retrieved from the archive. The absence of this info initiated the first geotechnical survey by Fugro and a site investigation for reassessment of the concrete foundation by Nebest. Nebest is an engineering company specialized in inspections of structures.

The survey to enhance the geotechnical data consisted of multiple CPTs (Cone Penetration Tests measuring cone resistance and sleeve friction): 1 CPT with measurement of the pore water pressure (CPTU), 4 magnetometer CPTs (CPTM) and 8 magnetometer CPTs with measurement of the pore water pressure (CPTMU). The purpose of executing the magnetometer CPTMs was to detect the pile tip level and therefore to confirm the pile length.

From the CPTs, two soil profiles (refer to Fig. 4.) could be distinguished, namely:

- General soil profile (CPTMU4, CPT7 and CPTMU8)
- Soil profile at the former dike of Hollands Diep river (CPT5 and CPT6)

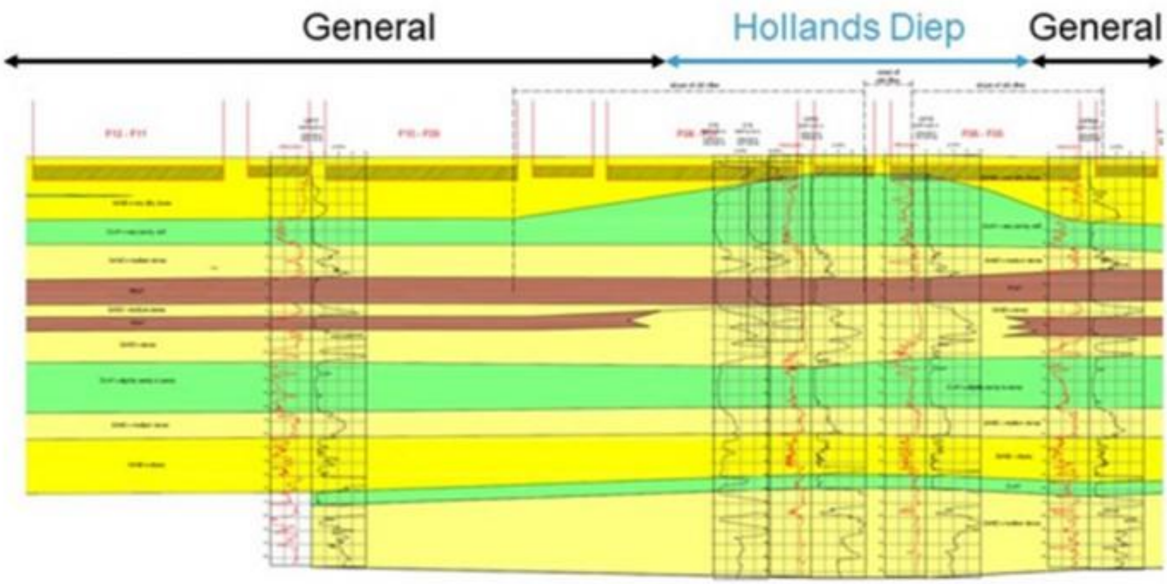

Fig. 4. Geotechnical soil profile indicating the location of the former dike of the Hollands Diep

Furnaces F05-F06 and F07-F08 are partly located on the former dike of the Hollands Diep. The other furnaces are on the left side of the dike. For the global soil conditions refer to Fig. 5.

Bovenkant laag [m NAP]			Laagdikte [m]	Bodembeschrijving
+4,4	à	-0,5	4,9	ZAND[1], sterk siltig, los
-0,5	à	-2,5	2,0	KLEI[1], sterk zandig, slap
-2,5	à	-4,0	1,5	ZAND, matig vast
-4,0	à	-6,0	2,0	VEEN
-6,0	à	-7,5	1,5	ZAND, matig vast
-7,5	à	-8,5	1,0	VEEN[2]
-8,5	à	-10,5	2,0	ZAND, vast
-10,5	à	-14,0	3,5	KLEI, zwak zandig tot zandig
-14,0	à	-16,3	2,3	ZAND, matig vast
-16,3	à	-20,3	4,0	ZAND, kleiig
-20,3	à	-21,1	0,8	KLEI[3]
-21,1	à	-32,5	11,4	ZAND, matig vast
-32,5	à	-35,8	3,3	ZAND, matig vast, doorsneden door kleilagen

1. De dikte van de topzandlaag en de kleilaag eronder is afhankelijk van de locatie binnen het projectgebied. Een dikkere kleilaag is aanwezig bij de voormalige dijk van het Hollands Diep.
2. Veenlaag niet aanwezig bij alle CPTs
3. Variërend in diepte tussen NAP -19,0 en NAP -21,5 m

Fig. 5. Global soil conditions under furnaces

Nebest conducted integrity tests based on destructive tests on the foundations. The objective of these tests was to determine and verify the quality and integrity status of the concrete slab, its outrigger foundations and associated piles. The outcome of the tests provided proof of the foundations and its piles being still in good condition after more than 50 years. The results provided the missing information to complement the info from the archive. With the excavation activities, the groundwater level was found at NAP +2.0 and NAP + 1.7.

Parallel to the engineering works at site related to foundations, the engineering contractor Technip Energies was selected for its modular design of above ground facilities. Considering the majority of projects always shows an increase in weight and size in the process of detailed engineering toward the final design, Shell set a requirement for Technip Energies in the Basis for Design to produce and adhere to a rigorous weight control program. The program is based on the ISO-19901-part 5, weight control during engineering and construction for offshore weight management, to ensure adequate accuracy in estimating the loads including contingencies and margins related to the capacities of the existing foundation. This program was deemed critical for the success of the project.

The weight program generated weight control sheets. The weight control sheets form the basis for the weight control report as well as the input for the STAAD calculation model, which subsequently generated the design loads on the pedestals of the furnace. These loads, together with all the available technical info, were implemented by Fugro and Nebest to generate their PLAXIS 3-D model (Fig. 4.), which was then used to calculate the maximum allowable pile bearing capacity. The outcome showed that the foundation loads were close to the maximum.

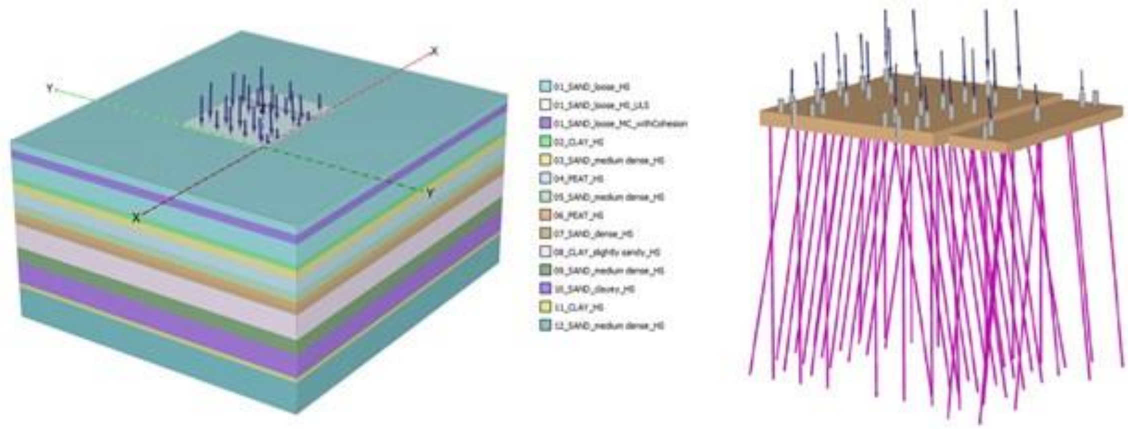

Fig. 4. PLAXIS 3D soil- and structure model.

As the loads were close to the maximum, Shell engaged with TNO in the person of Prof.dr.ir. R.D.J.M. Steenbergen to perform a probabilistic approach calculation on the piling capacity taking into consideration stochastic models for loadings, actual piling capacity and structural/geotechnical modelling of piling/soil system. The calculation compared the existing and the new situation and proved that the existing pile configuration was adequate of dealing with the new furnace loads, without modifications to the foundations, for the required period of 20 years as defined in the design premise.

Based on the engineering contractor’s modular design, in combination with the end select report on foundation re-use by Fugro and by Prof.dr.ir. R.D.J.M. Steenbergen, the Skyline project was granted the “GO” and entered the next phase.

Define and Execute phase (2020 – 2023) Focused investigations and analyses

With the project's path forward clear to re-use the foundations, the project required further investigations and calculations to confirm the structural adequacy of the foundations against the new loads without execution of any additional foundation reinforcement works.

Nebest further focused on the structural and concrete integrity of the foundations and piles providing more details and insights that confirmed and improved earlier assumptions in the previous project phases. The overall judgement was that the concrete foundations are in good condition. No integrity issues have been found, and based on the laboratory results and tests, no significant defect evolution is expected in the future in an equally conditioned environment and assuming the rest of the foundation is built in a similar way. Therefore, no additional corrective or preventive measures had to be taken.

In the design phase Fugro conducted another additional 37 CPTs in order to get better clarity and focused results per furnace pair on the dedicated geotechnical soil profile layer build up. The results of the CPTs showed it was required to further differentiate from the earlier determined soil profile conditions during the assess phase – see fig. 2. Therefore, a new soil profile, General Soil Profile number 2, has been introduced. See fig. 5.

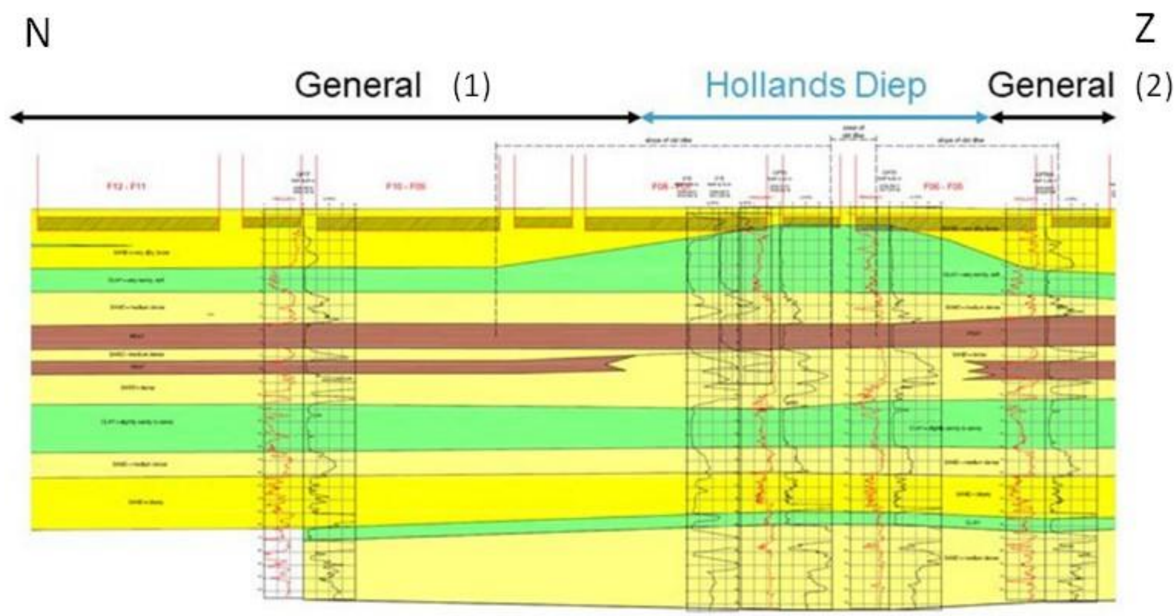

Fig. 5. Three soil profiles present under furnaces GP-1 (F9-F12) GP-2 (F5-F6) and HD (F7-F8)

It turned out that the General Soil Profile number 2 was the weakest of all three identified soil profiles. With Furnace 5 and Furnace 6 being located directly above GP-2 and first up for the revamp, this soil profile became instantly the governing case.

The calculations in the PLAXIS 3D model were continuously calibrated with new data from the new soil geometry, structural insights and the developing pedestal loads by Technip Energies – see Fig. 6. All data contributed thus to the accuracy of the model.

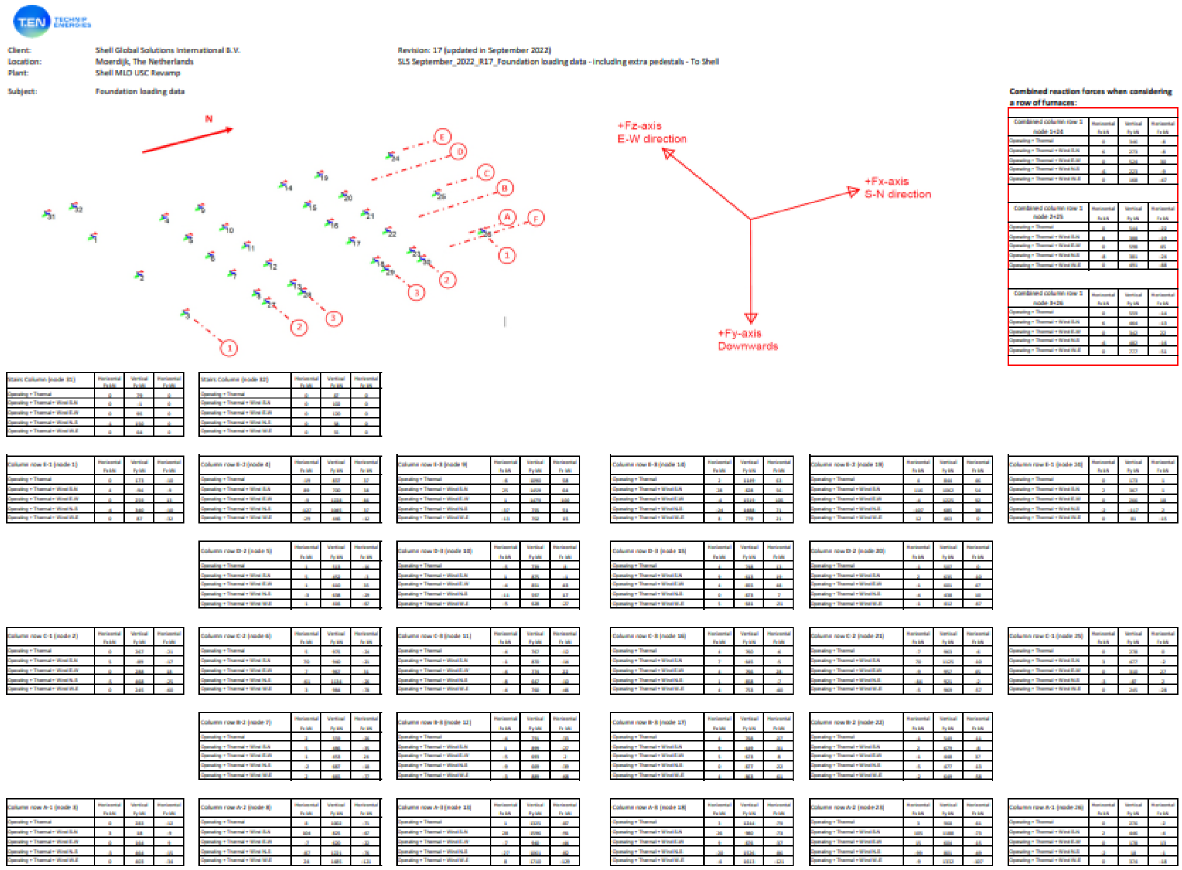

Fig. 6. Pedestal loads report revision 17

By autumn of 2020 the increased pedestal loads finally led to an unavoidable situation where the bending in the plate exceeded the requirement of the unity check being 1.0 (UC ≤ 1). The unity checks determined were uc =1,07 for the furnace plate and uc = 1,19 for the outrigger. A couple of piles also exceeded the uc =1, but with the vast majority being well below the unity check of 1.0, redistribution was anticipated for those piles.

With the project well in the define phase and at the verge of submitting the building permit, a preliminary modified design of the furnace foundation had been developed and thus submitted to the provincial authorities in 2021.

The violation of the threshold was not an ideal nor preferred condition the project envisaged to be in. The new foundation design could not be validated in the PLAXIS 3D model anymore as it had limitations to the ultimate limit state. Therefore, Shell sought Diana (NLyse) expertise to participate in the project by analyzing the structural capacity of existing foundations based on a physical, more realistic model (including non-linear behavior of the materials).

Pile bearing tests by Rapid Load testing

With the advanced 3D finite element model DIANA-FEA being deployed and the project started, the overseas construction of the furnace modules, the design and thus the weights developed into more maturity. An additional assurance step got initiated to even further fine tune the pile bearing capacities.

It was decided to do this with the method of a Rapid Load Test by Allnamics and described in NEN-EN-ISO 22477-10:2016 and NPR 7201:2017.

The area in the near vicinity of the furnaces close to the execution area would ideally haven been the preferred location to obtain the most reliable results. The project area turned out to be unsuitable as the underground is heavily populated with a large variety of underground infrastructure. To make the test reliable, and to be able to actually compare the furnace soil conditions for GP-2, a new location with the same soil characteristics was found opposite the furnaces along road 13.

For the rapid load test, five prefabricated piles of 400x400 and 20 m long have been installed at a depth of -14.5 NAP corresponding with the depth of the piles under the furnaces, and tested. These square 400 piles mimicked the original piles of square 380 the closest.

Fig. 7. Rapid load testing at Moerdijk

The test proved valuable as the results showed increased values compared to the calculated numbers by Fugro for friction and the pile bearing capacities. These results validated the figures calculated and used by Fugro/Nebest for the furnace foundations, meaning the project adopted a conservative calculation approach and thus creating additional capacity within the design.

Paal	CPT-nr	Test resultaten [kN]	Berekend [kN]	Verschil [%]
1	DKMP01	2394	2123	+13
2	DKMP02	3008	2080	+45
3	DKMP03	2494	1973	+26
4	DKMP04	2567	1703	+51
5	DKMP05	3340	2177	+53

Fig. 8. Test results of rapid load versus calculated values

DIANA (NLyse); final verification step

DIANA (NLyse) performed the final verification process on the foundations based on the latest revision (revision 17 from mid-September 2022) of the furnace pedestal loads (fig. 6) provided by Technip Energies. The loads derived from the weight program and STAAD calculation contained small margins and contingencies at the end of the construction process. The final weight of the furnace modules would be in the range of a 5% margin, which was anticipated and incorporated in the pedestal loads revision 17. Allowing the assurance of the furnace foundation by DIANA (NLyse) to be in parallel with construction of the modules at various locations around the world showed the advantage of both activities could be executed without delay to the project.

Diana (NLyse) used the earlier provided load cases, foundation model, pile stiffnesses and bearing capacity by Fugro and Nebest as input for her models. The nonlinear pile stiffness behavior up to failure had been provided by Fugro using its PLAXIS 3D model. Two finite element models have been produced, both linear and non-linear. The linear one has been used to determine the most normative (conservative) load cases from the five pedestal load combinations, these being:

- LC1: Static load - Self weight (SW) (normative for piles)
- LC2: wind S-N
- LC3: wind E-W
- LC4: wind N-S
- LC5: wind W-E

These most dominant load combinations are then applied to a non-linear model to obtain the final unity checks.

The results of the non-linear model initially showed by which factored ULS load the construction would fail. For example, in load case 1 it was determined that the outrigger foundation would fail at 1.25 x the ULS (near collapse state =NCS) load, which transfers into a unity check of 1/1.25 = 0.8.

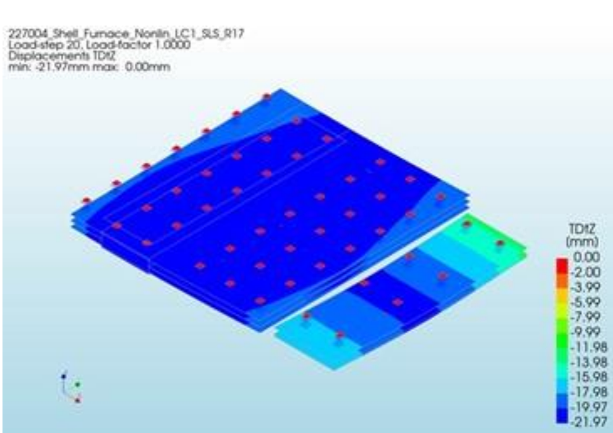

Fig. 9. Foundation displacement behavior

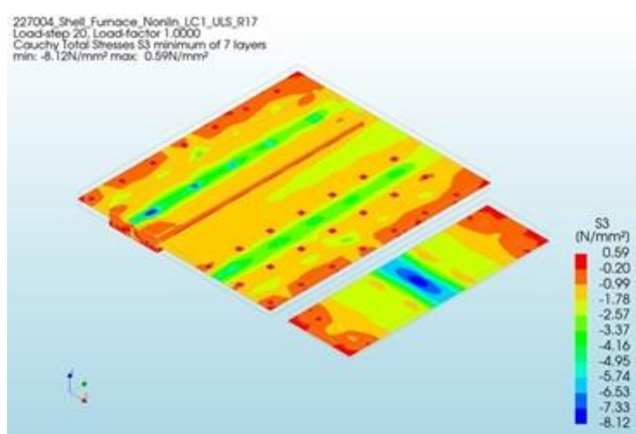

Fig. 10. Concrete compression stresses

Other load cases had similar outcomes of which the most dominant can be seen in fig. 11.

Unity Check	LC1	LC2	LC3	LC5
piles	0.71	0.54	0.60	0.72
Foundation	0.80	0.71	0.95	0.83
cracks	0.07	0.13	0.30	N/A

Fig. 11 The non-linear final unity checks based on the Furnace loads revision 17

With these great and positive unity check results in hand, the earlier submitted foundation upgrade to the provincial authorities, to enhance and structurally upgrade the existing foundation, could be disregarded. In addition, the calculation report showing the final figures has been uploaded into the authority system to follow the set procedures for a building permit by the provincial authorities, which was subsequently granted. In November 2022 the first furnace module has been successfully lifted into its final position. The last part, the chimney, is scheduled for end of February 2023.

This can be seen as a very big achievement by the entire Skyline project team as the complete demolition and rebuild took place in a live plant. It can be compared to open heart surgery, curing the patient without disrupting vital processes.

SUMMARY

Skyline is a multiyear project Shell started in 2017 when furnaces more than 40-years-old were reaching the end of life. It therefore had to replace / upgrade its Ultra Selective Cracking (USC) furnaces. Since replacement was required the opportunity arose to replace the existing furnace with a new, more efficient design, leading to a significant CO_2 emission reductions (10% for the total Moerdijk Chemicals park). Eight out of the 16 furnaces will be revamped based on a modular design approach as other options were too expensive.

The weight of the new modules needed to fit on the existing furnace foundations which date back from the late 1960s. Sufficient detailed information on the foundations is not available and a process has started to obtain this information via desktop study, destructive testing and geotechnical tests.

The test and study prove that the project is feasible during the assess and define process of the project. In order to remain feasible Shell prescribes the furnace engineering contractor to use a rigorous weight control program.

With the progress of the project, the geotechnical behavior of the foundation was analyzed with a PLAXIS 3D model, fed with additional data from additional investigations and the foundations loads from the engineering contractor. Mid 2020 the increase of the pedestal loads led to a unity check of more than one ($UC > 1$). The structural linear model is replaced by a 3D finite element non-linear model which is better capable to predict the elastic behavior.

As extra verification step, a rapid pile load test, is conducted which proves the used values for the pile bearing capacities are on the conservative side.

With this info and the final pedestal loads from Technip Energies, DIANA is capable of displaying that the old 1960 furnace foundations are well capable of accommodating the new increased furnace loads.

ACKNOWLEDGMENTS

The author would like to acknowledge permission to publish this paper from Technip Energies, Nebest BV, Fugro BV, NLyse formerly DIANA and Prof. R. Steenbergen (TNO). The support from Mr. A. van Seters of Fugro, Mr. B. Cotovanu and Mr. W Voogdt of Shell P&T is gratefully acknowledged.

Reference List

Some documents are used for internal and project use only and therefore not publicly available.

Fugro, 2021. Project Skyline – Shell Moerdijk – Pile tip levels of existing piles. Leidschendam 3p.

Fugro, 2022. Project Skyline – Shell Moerdijk – Overview of geotechnical and structural reports Part 1: Furnaces-rev. 24. Leidschendam 110p.

Fugro/ DIANA 2022. Project Skyline – Shell Moerdijk – WABO Fornuizen. Leidschendam/ Amersfoort P85.

Shell, 2019. Skyline basis for design. The Hague 105p.

NEN-EN-ISO 22477-10:2016 Geotechnical investigation and testing - Testing of geotechnical structures - Part 10: Testing of piles: rapid load testing

NPR 7201:2017. Geotechniek - Bepaling van het axiaal draagvermogen van funderingspalen door middel van proefbelastingen

ISO 19901-5:2021 Petroleum and natural gas industries — Specific requirements for offshore structures — Part 5: Weight management

Nebest, 2020. 200429 38070 v3 RapDef Shell Moerdijk onderzoek betonnen fundatie fornuizen 9_10 en 11_12 MLO 100. Vianen P. 37.