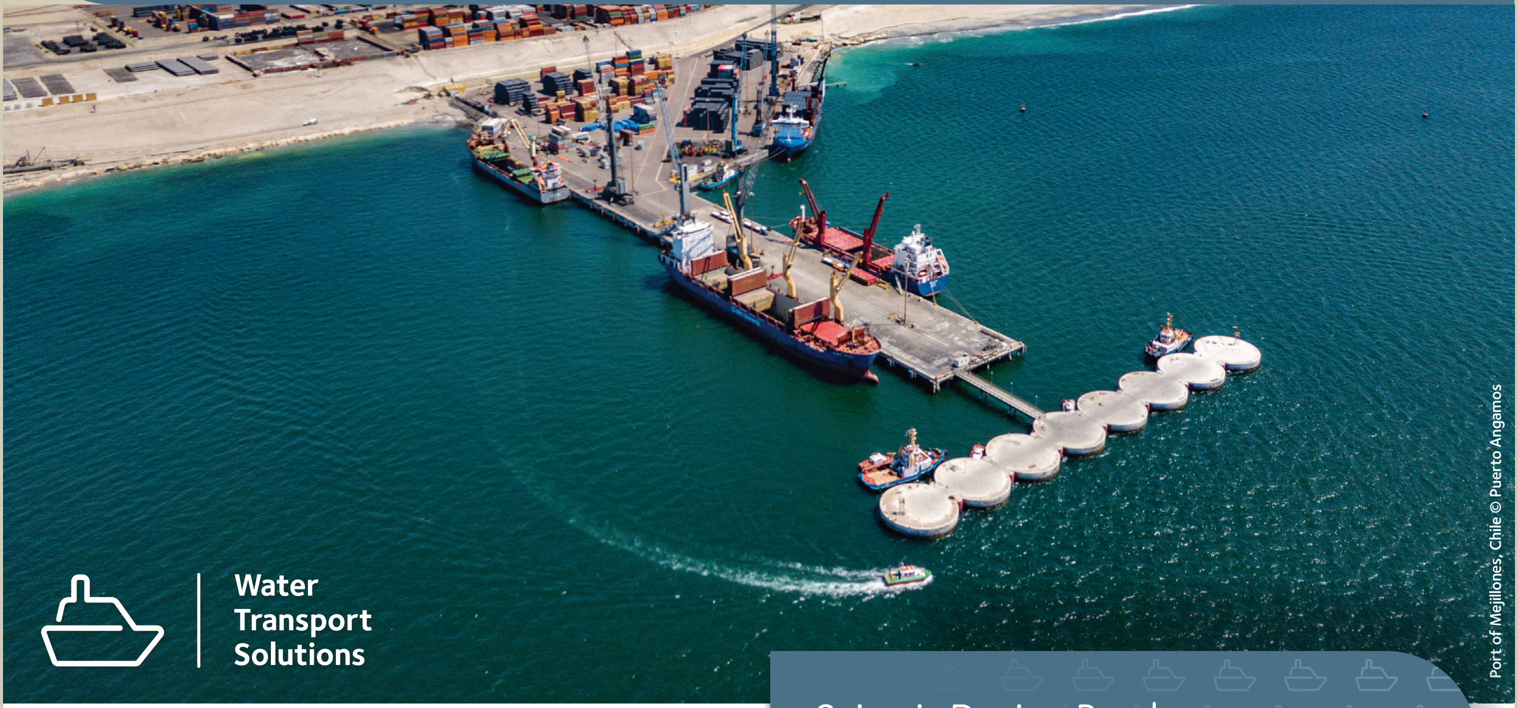
ArcelorMittal

Seismic design of sheet piles

Economic benefits of advanced design methods



Port of Mejillones, Chile © Puerto Angamos

Water Transport Solutions

Excellent performance of sheet piles under earthquake loading

Steel sheet piles are widely used for the construction of a variety of structures: quay walls and breakwaters in harbours, bank reinforcements on rivers and canals, urban infrastructures such as underpasses, as well as global hazard protection schemes. Sheet piles are also used in seismic areas and have shown their good performance when undergoing an earthquake.

Chile is the country that suffered the biggest earthquakes in recorded history, of which the 8.8 magnitude Maule earthquake that hit the Pacific coast in 2010. Many of the earthquakes that hit Chile in the last decade caused severe damages to the concrete-based ports of the country. Port of Mejillones, that was constructed in 2003 using the HZ/AZ combined wall for the quay wall and AS 500 straight web sheet piles for the breakwater, suffered no damages throughout many heavy earthquakes with magnitude of up to 7.7. All the involved parties in this project (Port authority, consultant, contractor and technical university) agreed that this port is a perfect example of the effectiveness of flexible sheet pile structures under extreme seismic conditions.

Although sheet piles have proven their performance under earthquake loading, a reluctance to use sheet piles in seismic areas remains among some designers. This concern may come from their experience of conventional design methods which do not favour flexible walls in seismic conditions. These design methods usually comprise of pseudo-static calculations using the Mononobe-Okabe theory (1931), based on the under-revision Eurocode EN 1998-5.

Seismic Design Brochure

For more information on the seismic design of sheet piles, a more comprehensive brochure provides a guideline for the dynamic design of sheet piles using Finite Element Modelling (FEM). It highlights the different aspects to be considered: model geometry, seismic motion, hydrodynamic loads...

This brochure also gives detailed information on the comparative study presented in this flyer (assumptions, study cases, procedure, results and conclusions).

Our technical experts are also available to assist you with the dynamic design of sheet piles using FEM.

A parametric study covering a wide spectrum of cases

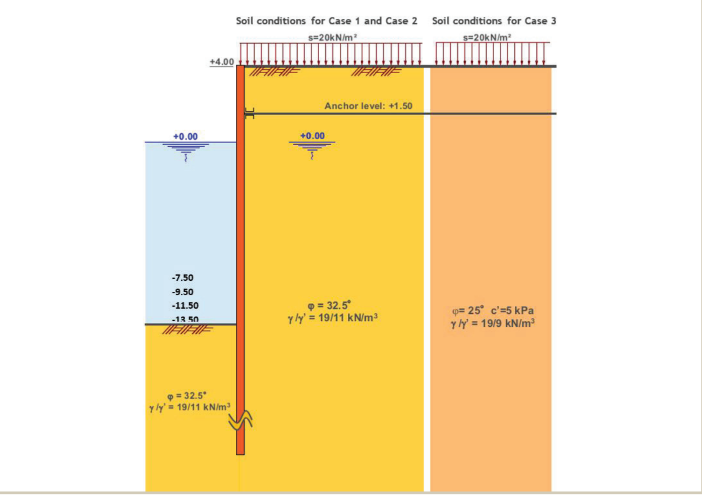
Numerical studies and physical experiments (centrifuge testing) have shown that these conventional methods of design are overestimating the loads on retaining walls, and especially in the case of flexible walls. EN 1998-5 allows for a reduction of the seismic action depending on the acceptable displacements, through a reduction factor “r”, but this factor is mainly thought for gravity walls and does not allow any reduction for anchored walls, including sheet pile walls despite their inherent property of ductility.

Today, powerful design tools using Finite Element Modeling (FEM) allow dynamic calculations that can accurately predict the behaviour of the retaining walls undergoing different seismic loadings. This type of calculations gives precise information about the internal forces, the deformations, the increase in pore water pressures and the expected mode of failure to be avoided. It also permits a correct consideration of some features like the hydrodynamic loading through added masses.

In order to examine the two methods of design, ArcelorMittal contracted Spanish engineering consultancy SENER to carry out a parametric study on a wide spectrum of studied cases (4 water depths, 4 seismic accelerations, 2 soil conditions), comparing the conventional pseudo-static method based on EN 1998-5 using an elasto-plastic subgrade reaction software, and the fully dynamic advanced method using a FEM software.

Cases	Soil	Sea bed level	Acceleration	Spectra according to EN 1998-5
Case 1.1	Sand	-7.5	0.10 g	Type 2
Case 1.2	Sand	-9.5	0.10 g	Type 2
Case 2.1.1	Sand	-7.5	0.30 g	Type 1
Case 2.1.2	Sand	-9.5	0.30 g	Type 1
Case 2.1.3	Sand	-11.5	0.30 g	Type 1
Case 2.1.4	Sand	-13.5	0.30 g	Type 1
Case 2.2.1	Sand	-7.5	0.40 g	Type 1
Case 2.2.2	Sand	-9.5	0.40 g	Type 1
Case 2.2.3	Sand	-11.5	0.40 g	Type 1
Case 2.2.4	Sand	-13.5	0.40 g	Type 1
Case 3	Silty clay	-9.5	0.50 g	Type 1

Design cases considered in the study performed by SENER.



Design cross sections.

Advanced seismic design methods allow up to 50% cost savings

The study considered 11 cases crossing different soil conditions, seismic accelerations and water depths (see table), in order to draw clear conclusions on the advantages and disadvantages of each design method.

The pseudo-static design is performed using the elasto-plastic subgrade reaction software RIDO. The seismic action is considered by modifying the earth pressure coefficients K_a and K_p based on the well-known Mononobe-Okabe formula. This results in an increase of the active pressure behind the wall and a decrease of the passive pressure in front of the wall.

The dynamic design is carried out using the FEM software Plaxis 2D. The seismic action is considered by means of seismic signals introduced at the bottom of the 2D model. The signals used were fitted to the spectra from EN 1998-1 and scaled to the respective Peak Ground Acceleration (PGA) of the studied case.

All the cases studied showed substantial optimization potential when using the FEM design. The bending moments in pseudo-static design are 40 % to 126 % higher than the FEM design. When considering the respective sheet pile sections, the resulting material cost savings are up to 28 % for low to moderate earthquakes (0.10 g) and up to 48 % for strong earthquakes (0.30 g-0.40 g).

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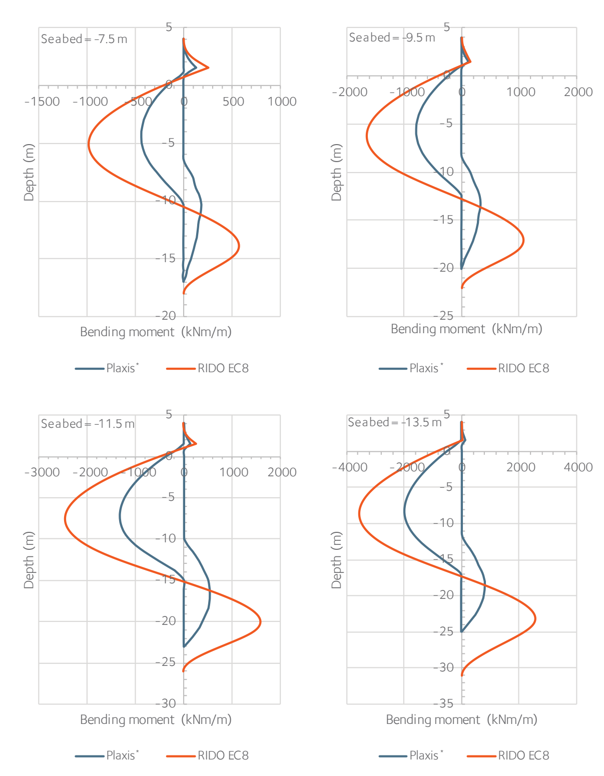
Bending moment forces for case 2.1. (PGA = 0.30 g)



* *For Plaxis dynamic calculations, the envelope of the bending moments from all the calculations steps is shown.*

Proper consideration of hydrodynamic loads is necessary for an economical solution

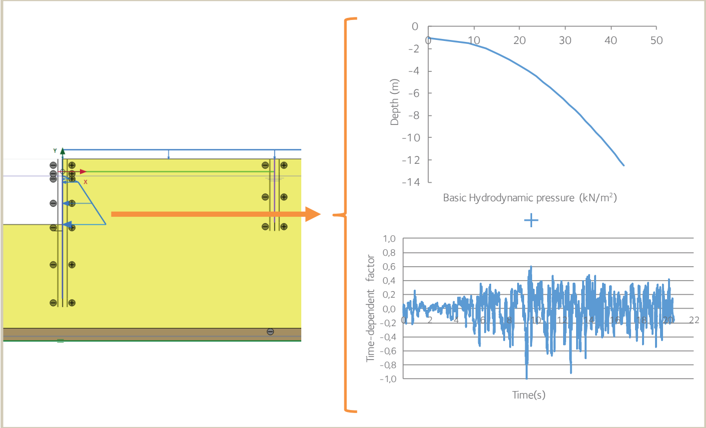
The common practice for taking into account hydrodynamic loads is to consider a pseudo-static load calculated from EN 1998-5 (Westergaard formula). This translates into considering a permanent load from the water, for the whole duration of the earthquake, on the shaking quay wall. SENER carried out FEM and Computational Fluid Dynamics (CFD) calculations to measure the impact of hydrodynamic loads on a sheet pile wall during the seismic motion.

The CFD calculations considered soil-fluid interactions under dynamic analyses. The hydrodynamic load calculated at an instant “t” of the earthquake showed a very good match with the Westergaard load calculated with the seismic acceleration at that same instant. This means that the hydrodynamic load mentioned in EN 1998-5, which uses the Peak Ground Acceleration, represents the higher bound envelope of the hydrodynamic loads. If this higher bound envelope load is considered through the entire duration of the earthquake, it is evident that this will lead to an overestimation of the hydrodynamic loads’ effect.

The FEM calculations carried out using Plaxis 2D compared the results obtained when using the “traditional” Westergaard load with those obtained when using a realistic time-dependent variable load (through a dynamic load or through added masses). The results showed an increase of 24.5 % in the bending moment, with respect to the effects from purely the seismic action, when using the traditional Westergaard load compared to 4 % when using the instantaneous load. In this case study, considering a realistic hydrodynamic load translated into a material cost saving of 14 % when considering the corresponding sheet pile sections.

	Bending moment		Corresponding sheet pile section	Material cost savings
	Value	Relative increment		
	kNm/m	%	-	%
Seismic	1761	-	-	-
Seismic + Traditional Westergaard	2193	24.50%	AZ 52-700	-
Seismic + Time-dependent Westergaard	1830	3.90%	AZ 44-700N	**14%**

Bending moment comparison for a 15.5 m retaining wall undergoing a 0.4 g PGA earthquake.



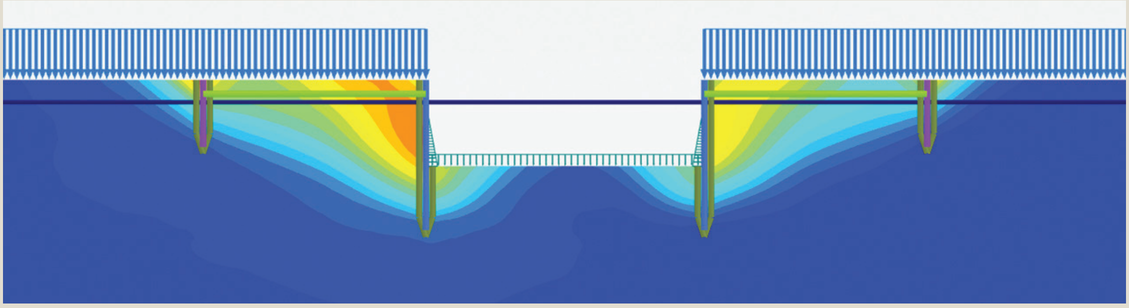
Time-dependent hydrodynamic load introduced in the Plaxis model.

Resulting sheet pile sections for case 2.1 (PGA 0.30 g) and consequent savings

Cases	Pseudo-static (EN 1998-5)		FEM Design		Material cost savings
	Length	Section	Length	Section	
	m	-	m	-	
Case 2.1.1	22	AZ 25-800	21	AZ 18-800*	**25%**
Case 2.1.2	26	AZ 36-700N	24	AZ 22-800	**34%**
Case 2.1.3	30	AZ 52-700	27	AZ 30-750	**48%**
Case 2.1.4	35	HZ 1080M C-12 / AZ 25-800	29	AZ 42-700N	**46%**

** Resulting section based on bending moment capacity. The recommended section might be different based on driveability and local conditions.*

Mirrored Plaxis model used for the dynamic design




Port of La Spezia, Italy © Ph. Enrico Amici

> “The wind does not break the tree that bends”
> *Tanzanian proverb*

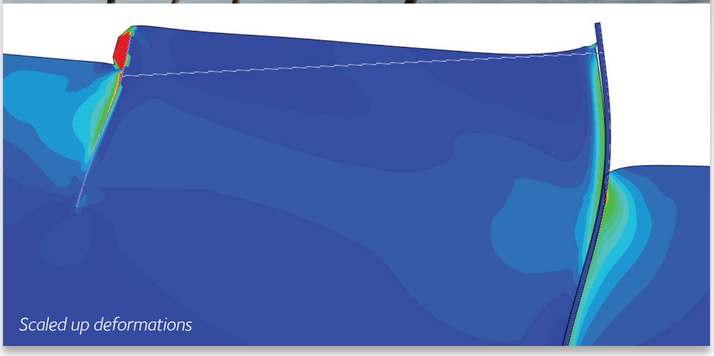
Italian standard NTC 2018 rewarding the flexbility of sheet piles

After pinpointing the overestimation that can result from performing pseudo-static calculations using EN 1998-5, the study analyzed what the recent Italian seismic standard NTC 2018 has to offer in this matter.

NTC 2018 follows the same philosophy as EN 1998-5 for pseudo-static calculations but introduces many amendments on the parameters defining the seismic action. The main changes concern the seismic reduction coefficient that accounts for the deformability of the structure and the deformability of the soil among other things. In practice, NTC 2018 allows further reduction of the seismic coefficient for more flexible walls.

SENER carried out the pseudo-static calculations using NTC 2018 as a reference standard for the seismic coefficient.
The resulting sheet pile sections were lighter than those obtained with EN 1998-5, and closer to those from dynamic FEM calculations.

These results confirm that the Eurocode EN 1998-5 does not reveal the true potential of sheet piles in seismic areas.
This potential can be fully embraced through advanced design methods and more recent standards.


Scaled up deformations

Cases	Pseudo-static (NTC 2018)		FEM Design		Material cost savings
	Length	Section	Length	Section	
	m	-	m	-	
Case 2.1.1	22	AZ 20-800	21	AZ 18-800*	**13%**
Case 2.1.2	26	AZ 27-800	24	AZ 22-800	**19%**
Case 2.1.3	29	AZ 36-700N	27	AZ 30-750	**20%**
Case 2.1.4	33	AZ 52-700	29	AZ 42-700N	**25%**

** Resulting section based on bending moment capacity. The recommended section might be different based on driveability and local conditions.*