Displacement of marine pipelines

By

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Abstract

Marine pipelines are used to transport seawater, effluent, and bulk oil and gas products. Their potential displacement is significant because it affects the pipeline network's integrity in a very challenging environment. The main purpose of this study is to assess the different methods used to calculate marine pipeline displacement and select the most appropriate option.

An overview is given of two materials used for the manufacture of marine pipelines: metal and non-metal pipes. The metal pipes are commonly made of carbon steel, but they can be constructed from stainless steel or a duplex in some harsh service conditions. The most used non-metal pipes in the oil and gas industry are HDPE, GRP, and GRE. They are more common for large diameter pipelines associated with power station cooling waters. Unbonded non-metal pipelines are standard oil and gas industry composite pipelines, while bonded non-metal hoses are associated with tanker loading and unloading activities. Concrete is also a material used in pipe construction. However, it is not discussed in this study.

This study focuses on eight methods: The Force Balance Method, the DNV-RP-E305 code's Simplified Stability Analysis, Generalized Stability, and Dynamic Analysis, the DNV-RP-F109 code's Absolute Lateral Static Stability method, Generalized Lateral Stability Method and Dynamic Lateral Stability Analysis and lastly, the Scandinavian Method. All these methods are discussed, analysed, compared to each other, and a guideline is given for their applications.

The primary methodology for comparing the eight methods was using the results of a case study that determined its pipes' displacement through the Scandinavian Method. The pipe characteristics (mainly diameter) of that project were then used to determine the displacements that would have been produced by the other methods. There are also calculations done on the required pipe weight for the pipe by using each method. The results produced by each method were compared to each other and used as inputs for a Multi-Criteria Analysis (MCA) which was also performed on the Methods. Recommendations were made based on the results of the MCA. The two Dynamic Analysis methods were excluded from this entire section because they would have required finite element analysis and dynamic modelling, which are excluded from the scope of this study

In the recommendations, the DNV-RP-F109 code's Generalized Lateral Stability Method is proposed since it scored the highest in the MCA. However, this is subject to the condition that all the method's requirements are met, and the method is relevant to the specific case study.

Opsomming

Mariene pypleidings word gebruik om seewater, uitvloeisel en grootmaat olie- en gasprodukte te vervoer. Hul potensiële verplasing is beduidend omdat dit die pyplynnetwerk se integriteit in 'n baie uitdagende omgewing beïnvloed. Die hoofdoel van hierdie studie is om die verskillende metodes wat gebruik word om mariene pyplyn verplasing te bereken te assesseer en die mees geskikte opsie te kies.

'n Oorsig word gegee van twee materiale wat gebruik word vir die vervaardiging van mariene pypleidings: metaal- en nie-metaalpype. Die metaalpype word gewoonlik van koolstofstaal gemaak, maar hulle kan in sommige moeilike diensomstandighede van vlekvrye staal of 'n dupleks vervaardig word. Die mees gebruikte nie-metaalpype in die olie- en gasbedryf is HDPE, GRP en GRE. Hulle is meer algemeen vir pypleidings met 'n groot deursnee wat met kragstasie-verkoelingswater geassosieer word. Ongebonde nie-metaalpypleidings is standaard saamgestelde pypleidings in die olie- en gasbedryf, terwyl gebonde nie-metaalpype geassosieer word met tenkwalaai- en aflaaiaktiwiteite. Beton is ook 'n materiaal wat in pypkonstruksie gebruik word. Dit word egter nie in hierdie studie bespreek nie.

Hierdie studie fokus op agt metodes: Die Kragbalansmetode, die DNV-RP-E305-kode se Vereenvoudigde Stabiliteitsanalise, Algemene Stabiliteit en Dinamiese Analise, die DNV-RP-F109-kode se Absolute Laterale Statiese Stabiliteitsmetode, Veralgemeende Laterale Stabiliteitsmetode en Dinamiese Laterale Stabiliteitsanalise en laastens die Skandinawiese Metode. Al hierdie metodes word bespreek, ontleed, met mekaar vergelyk, en 'n riglyn word gegee vir hul toepassings

Die primêre metodologie vir die vergelyking van die agt metodes was die gebruik van die resultate van 'n gevallestudie wat sy pype se verplasing deur die Skandinawiese Metode bepaal het. Die pyp-eienskappe (hoofsaaklik deursnee) van daardie projek is dan gebruik om die verplasings te bepaal wat deur die ander metodes geproduseer sou word. Daar word ook berekeninge gedoen oor die vereiste pypgewig vir die pyp deur elke metode te gebruik. Die resultate wat deur elke metode geproduseer is, is met mekaar vergelyk, en gebruik as insette vir 'n Multi-Kriteria Analise (MCA) wat ook op die Metodes uitgevoer is. Aanbevelings is gemaak op grond van die resultate van die MCA. Die twee Dinamiese Analise-metodes is uitgesluit van hierdie hele afdeling omdat hulle eindige-element-analise en dinamiese modellering sou vereis het, wat uitgesluit is van die bestek van hierdie studie.

In die aanbevelings word die DNV-RP-F109-kode se algemene laterale stabiliteitsmetode voorgestel aangesien dit die hoogste in die MCA behaal het. Dit is egter onderhewig aan die voorwaarde dat aan al die metode se vereistes voldoen word, en die metode is eintlik relevant tot die spesifieke gevallestudie.

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Table of Contents

Abstract iii
Opsomming iv
Acknowledgments v
List of Tables vii
List of Figures viii
List of Symbols and Abbreviations ix
1. Introduction 11
1.1 Objectives 12
1.2 Scope 12
1.3 Layout of Thesis 13
2. Literature Study 14
2.1 Methodology 14
2.2 Marine Pipelines 14
2.2.1 Metal Pipes 14
2.2.2 Non-metal Marine Pipelines 15
2.3 Pipe Failure Modes 17
2.3.1 Buckling 17
2.3.2 Fracture 18
2.3.3 Vertical displacement 18
2.3.4 Fatigue 18
2.4 Wave Force Interactions with a Pipeline 18
2.5 Methods of Calculating Displacement 19
2.5.1 Force Balance Method 20
2.5.2 Scandinavian Design 21
2.5.3 DNV-RP-E305 23
2.5.4 DNV-RP-F109 34
3. Methodology 63
4. Case Study 64
4.1 Case Study Results 65
4.1.1 Site Data 65
4.1.2 Case Study Assumptions: 65
4.1.3 Weight Calculations 65
4.2 Results from applying other methods to case study 69
4.2.1 Displacement Results 69
4.2.2 Weighting Results 69
5. Multi-Criteria Analysis 74
5.1 Overview 74

5.2 Scoring Method 74
5.3 MCA Results 74
5.4 Discussion on MCA results 75
5.5 MCA Sensitivity Analysis 77
5.5.1 MCA Alt 1 – Displacement Allowance 77
5.5.2 MCA Alt 2 – Required Weighting 78
6. Discussion 80
7. Conclusions and Recommendations 81
8. Referencing 83

List of Tables

Table 2-1: Minimum weight, L_{stable} / $(2 + M)^2$, for pipe on sand, K ≥ 10 (DNV-RP-F109) 39
Table 2-2: Minimum weight, L_{stable} / $(2 + M)^2$, for pipe on sand, K ≤ 5 (DNV-RP-F109) 40
Table 2-3: Minimum weight, L_{10} / $(2 + M)^2$, for pipe on sand (DNV-RP-F109) 42
Table 2-4: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$ for pipe on clay, Gc = 0.0556 (DNV-RP-F109) 44
Table 2-5: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, Gc = 0.111 (DNV-RP-F109) 47
Table 2-6: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, G_c = 0.222 (DNV-RP-F109) 50
Table 2-7: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, G_c = 0.556 (DNV-RP-F109) 53
Table 2-8: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, G_c = 1.11 (DNV-RP-F109) 56
Table 2-9: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, G_c = 2.78 (DNV-RP-F109) 59
Table 4-1: Lateral Displacements along sections of the 0.9m OD pipeline 68
Table 4-2: Displacement Allowances of Different Methods for the Case Study 69
Table 4-3: Peak horizontal load coefficients 71
Table 4-4: Peak vertical load coefficients 71
Table 4-5: Summary of the results of Required Weight Calculations 73
Table 5-1: Basis for Scoring Criteria 74
Table 5-2: Results of the Multi-Criteria Analysis on the Displacement Methods 75
Table 5-3: MCA Sensitivity Analysis weighted to prioritize Displacement Allowance 77
Table 5-4: MCA Sensitivity Analysis weighted to prioritize Flexibility 78

List of Figures

Figure 2-1: The corresponding Generalized Weight Parameter L and Bending Strain versus K of M values (Marineman, 2015) 26
Figure 2-2: L and ϵ' vs. K of M values when δ = 10 and T = 1000 (Marineman, 2015)......... 27
Figure 2-3: L and ϵ' vs. K of M values when δ = 20 and T = 500 (Marineman, 2015)........... 28
Figure 2-4: L and ϵ' vs. K of M values when δ = 20 and T = 1000 (Marineman, 2015)......... 29
Figure 2-5: L and ϵ' vs. K of M values when δ = 40 and T = 500 (Marineman, 2015)........... 30
Figure 2-6: L and ϵ' vs. K of M values when δ = 40 and T = 1000 (Marineman, 2015)......... 31
Figure 2-7: A stable pipe's Generalized Weight Parameter L (δ = 0). (Marineman, 2015) ... 32
Figure 2-8: f_{ws} vs. Soil Density, G (Marineman, 2015) 32
Figure 2-9: Required weight for μ = 0.6 and F_R = 0 (DNV-RP-F109) 36
Figure 2-10: Required weight for μ = 0.2 and F_R = 0 (DNV-RP-F109) 37
Figure 2-11: Minimum weight, L_{stable} / $(2+M)^2$, for pipe on sand (DNV-RP-F109, 2017)........ 41
Figure 2-12: Minimum weight, L_{10} / $(2+M)^2$, for pipe on sand (DNV-RP-F109, 2017) 43
Figure 2-13: Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 0.0556 (DNV-RP-F109, 2017)... 45
Figure 2-14: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.003, Gc = 0.0556 (DNV-RP-F109, 2017)... 46
Figure 2-15: Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 0.0111 (DNV-RP-F109, 2017)... 48
Figure 2-16: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.024, Gc = 0.111 (DNV-RP-F109, 2017)... 49
Figure 2-17: Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 0.222 (DNV-RP-F109, 2017)... 51
Figure 2-18: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.024, Gc = 0.222 (DNV-RP-F109, 2017)... 52
Figure 2-19:Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 0.556 (DNV-RP-F109, 2017)... 54
Figure 2-20: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.024, Gc = 0.556 (DNV-RP-F109, 2017)... 55
Figure 2-21: Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 1.11 (DNV-RP-F109, 2017) 57
Figure 2-22: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.024, Gc = 1.11 (DNV-RP-F109, 2017)... 58
Figure 2-23: Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 2.78 (DNV-RP-F109, 2017) 60
Figure 2-24: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.024, Gc = 2.78 (DNV-RP-F109, 2017)... 61

List of Symbols and Abbreviations

α	Angle of inclination of the wave orthogonal relative to the pipeline axis
ρ	Ambient water density
ρ_w	Mass density of sea water
ρ_s	Mass density of sand soil material
μ	Coulomb friction factor
γ'_s	Submerged unit soil weight
γ_s	Dry unit soil weight
γ_w	Safety factor
τ	Number of oscillations in the design bottom velocity spectrum
δ/δt	Differentiation with respect to time
3D	Three dimension
AGA	American Gas Association
BS	British Standards 8010
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Inertia coefficient
CWC	Concrete Weight Coating
C^*_Y	Horizontal peak load coefficients
C^*_Z	Vertical peak load coefficients
D	Outer diameter of the pipe
DNV-RP	Det Norske Veritas – Recommended Practice
du/dt	Water particle acceleration normal to the pipe
FE	Finite Element
F_R	Passive resistance
F_L	Vertical Lift force
F_D	Drag force
F_H	Horizontal hydrodynamic load
F_M	Inertia Force
F_w	Calibration factor
G_s	Sand soil strength parameter
G_c	Clay soil strength parameter
GRE	Glass Reinforced Epoxy
GRP	Glass Reinforced Pipe

HPDE	High-density polyethylene
JIP	Joint Industry Project
K	Significant Keulegan-Carpenter number
L	Significant Weight Parameter
m	meter
M	Steady to oscillatory velocity ration for design spectrum
mm	millimetre
MCA	Multi-Criteria Analysis
M_{disp}	the mass of water displaced by the pipe (per m length)
N	Spectral acceleration factor
O&G	Oil and Gas
PIPESTAB	Pipeline Stability (project)
$r_{tot,Y}$	Total horizontal load reduction
$r_{tot,z}$	Total vertical load reduction
S_U	Undrained clay soil strength
T	Sea state duration
T_U	Near bottom zero up-crossing period due to a given surface sea state
u	Instantaneous (time-dependent) flow velocity
U	Horizontal velocity as a function of time
ú	Horizontal acceleration as a function of time
U^*	Oscillatory velocity amplitude for single design oscillation, normal to the pipe
U_c	steady current component in the boundary layer normal to the pipe
U_s	Near bottom significant velocity normal to the pipeline due to a given surface sea state
UV	Ultra Violet
V^*	Steady current velocity associated with design oscillation, normal to the pipe
W_s	Pipeline submerged weight
y	Inline displacement of the pipe
$Y_{allowable}$	The allowed dimensionless lateral displacement scaled to the pipe diameter.

1. Introduction

Marine pipelines are used to transport seawater, effluent, and bulk oil and gas products. They are usually manufactured from steel, high-density polyethylene (HDPE) or composite pipes. They transport oil and gas from subsea wells to the platform and the coast for further process and distribution. There are also large pipelines for transporting gas or oil from one country to another. Marine pipelines are also used in several other applications including at marine outfalls, desalination applications and power plants.

The effect of the displacement of marine pipelines is significant because it affects the integrity of the pipeline network in a very challenging environment. Repairs and inspections are expensive for underwater pipelines. Thus, it is best to select pipe designs that will limit maintenance required after construction. When excessive displacement results in pipe rupture during operation, it causes production loss for downstream operations. Pipelines more than often represent a single point failure of the system. The most critical impact is the environmental impact of spillage, especially in the case of the oil and gas industry and effluent discharge.

The primary purpose of this thesis is to assess the different methods used to calculate the horizontal stability of marine pipelines on the seabed. The study could also look at vertical stability, however, for the purpose of staying within the limitations of this study's scope, the focus will be on horizontal stability only. Due to the different industries and environmental conditions found in different locations, no single specific method is best applied to all situations. Different industries use different methods of assessment. The DNV-RP-F109 is mostly used in the oil industry, while the Force and Scandinavian methods are more common in plastic pipeline industries. However, DNV-RP-F109 is also applied in these industries. The marine application is seemingly a function of the Designer's choice of method.

The PD-8010-2 (2004) Standard states that "a two-dimensional analysis method is acceptable for determining the stability of a pipeline. In areas where excessive stabilization is predicted, a more complex three-dimensional analysis method may be used." For the two-dimensional analysis method, the Standard recommends the approaches in DNV-OS-F101 and DNV-RP-E305. The Standard also recommends the American Gas Association publication "Submarine pipeline on-bottom stability" in addition to the approaches in DNV-OS-F101 and DNV-RP-E305 for the three-dimensional analysis method.

The SRPS EN ISO 13628-11 (2010) Standard recommends the “dynamic analysis involving a full dynamic simulation of the pipe resting on the seabed and including modelling of soil resistance, hydrodynamic forces, boundary conditions and dynamic responses” or the “generalized stability analysis based on non-dimensional curves derived from a series of runs with a dynamic-response model” or the “simplified stability analysis based on a quasi-static balance of forces acting on the pipe.”

Among several other factors, choosing a technique requires comprehensive research on the current site conditions, pipe material, the function of the pipeline, and its life expectancy. All these factors determine which method will be most relevant for that specific pipeline. The selection is also based on the designer's choice of method. The study compares the models to identify the differences and identify under different scenarios if some are more conservative than others or not valid.

1.1 Objectives

This study aims to make a comparison of several methods that can be used for predicting the displacement of marine pipelines because of wave action.
The objectives of the study are as follows:

- Provide information on some of the materials that can be used for the construction of marine pipelines
- Give a brief overview on the other failure modes that pipes can experience besides pipe displacement.
- Briefly discuss wave force interactions with a pipeline
- Utilize the results of displacements and pipe weightings calculated for a case study as inputs for a Multi-Criteria Analysis
- Make recommendations on a proposed method based on all the results and theory provided

1.2 Scope

This study will be focusing specifically on marine pipelines and will not be relevant for pipelines used outside the marine environment. While the focus of this study is more specific to the oil and gas industry, the case study is based on a marine application that is not in the oil and gas industry. The methods in this study are used in non-metal and metal pipelines. While concrete pipes can be used in marine applications, they are not included in the scope of this study.

Focus will be on lateral (horizontal) displacement. While a brief overview is given on vertical displacement and other pipe failure modes in the literature study, the methods for displacement calculation are limited to lateral displacement. This study focuses more on methods that can determine displacement without requiring modelling. Hence, Finite Element analysis is excluded from the scope. Brief overviews are given for the two dynamic modelling options (Dynamic Analysis of DNV-RP-E305 and the Dynamic Lateral Stability Analysis of DNV-RP-F109) but their finite element analyses have not been included in those sections.

1.3 Layout of Thesis

The literature study starts with providing overviews on two types of marine pipe materials: metal and non-metal pipelines. (while concrete pipes can also be used in marine applications, they are not included in the scope of this study). This is followed by a brief overview on four types of pipe failure modes: buckling, fracture, vertical displacement, and fatigue. Finally, the wave force interactions with a pipeline are detailed just before getting into the focus of this study: Methods of determining pipe Displacement.

The methods that are discussed include the Force Balance Method, the Scandinavian Design, the Simplified Stability Analysis, Generalized Stability Analysis and Dynamic Analysis in the DNV-RP-E305 code and the Absolute Lateral Static Stability Method, Generalized Lateral Stability Method and Dynamic Lateral Stability Analysis in the DNV-RP-F109 code.

The Methodology explains that there is a case study which used one of the methods (Scandinavian Method) in conjunction with two programs to determine the displacement of two HDPE pipes. There was also a required weighting calculation done during the case study for one of the pipes (0.9m OD pipe). The displacement and required pipe weighting results produced during the Case Study are then compared with the Results produced by applying the displacement and required pipe weighting calculations of all the Methods to the same case study.

The results of all these calculations are then used as inputs for the Multi-Criteria Analysis, which reveals the recommended method as the one which produced the highest scores during the MCA and two Sensitivity Analyses.
Finally, the Thesis is closed off with a Discussion, which is followed by Conclusions and Recommendations.

2. Literature Study

2.1 Methodology

The Literature Study was carried out by using several sources to provide information on two types of pipe material: metal and non-metal pipes, four pipe failure modes, wave force interactions with a pipeline and methods of determining lateral pipe displacement.

The literature study references the PD-8010-2 (2004) and SRPS EN ISO 13628-11 (2010) Standards, (Technip, 2015), Kirkvik H. (2013) and Bai (2014) for the section on metal and non-metal pipelines. The PD-8010-2 (2004) Standard is also referenced on the failure modes that a pipeline can experience in addition to lateral displacement. Thereafter, in the discussion on methods of calculating pipe displacement, Chukwu O.D. et al (2016) and Cumming G. et al (2009) are referenced for the Force Balance Method and references several times throughout the DNV-RP-E305 and DNV-RP-F109 methods. Marineman, (2015) is also the main source used in the DNV methods.

The Literature ends with detailing the analyses that have been made by several researchers on the methods. These researchers include: Chukwu O.D. et al (2016) Cumming G. et al (2009), Bai (2014), Bai (2005), Amlashi H. (2017), Damgaard, J.S. et al (2006) and (Carneiro D. et al (2015).

2.2 Marine Pipelines

As stipulated in the scope, this study is only focusing on two types of subsea pipelines: metal and non-metal pipes mainly used in the oil and gas industry.

2.2.1 Metal Pipes

The most used subsea metal pipes are made of carbon steel material. However, stainless steel can also be used for subsea pipelines. BS8010 differentiates between thin and thick wall pipes, but both are used for subsea systems.

The industry's general trend is to use carbon steel as it is the cheapest in all aspects. If justified by the corrosive nature of the fluid service, or possibly high-pressure or temperature, it must be considered to move to a higher-grade carbon steel (which has a reduced production cost compared to stainless steel). Stainless steel is the last port of call.

Bai (2014) recommends the use of carbon steel, low alloy martensitic steels, austenitic steels, lined pipe, and duplex stainless steels for “sweet environments” and for “sour environments:” carbon steel, duplex stainless steels, lined pipe, and nickel alloy-clad pipes are recommended.

Material grades are selected based on the following factors (Bai, 2014):

- Weldability
- Resistance to corrosion effects
- Weight requirement
- Cost.

The material grade choice has cost implications on the following (Bai, 2014):

1. Fabrication of pipeline

   The higher the steel grade, the more expensive it is per volume (weight). However, the increasing grade may reduce pipe wall thickness, which results in an overall decrease in fabrication cost.

2. Installation

   Lower-grade steel pipelines have lower installation costs: high-grade steels are more difficult to weld than lower lay rates. However, high-grade steel in very deep water is more suitable since the pipe weight reduction lowers lay tension.

3. Operation

   The pipeline may be experiencing internal corrosion, erosion, and Hydrogen Sulphide induced corrosion.

2.2.2 Non-metal Marine Pipelines

The SRPS EN ISO 13628-11 Standard states that the applications of onshore and offshore non-metal pipes are categorized into static and dynamic applications.

For static applications, fixed jacket-riser service and flowline are the main purposes of non-metal pipe use. Some examples of applications in which a simplified flowline design or installation are achieved from using non-metal pipes include applications with uneven seabed, in deep water or severe environments and mudslides. The range of internal diameter for the non-metal pipes is 0.05m to 0.5m. However, the internal diameters of some low-pressure bonded non-metal pipes e.g., oil suction and discharge hoses, can go up to 0.91m. (SRPS EN ISO 13628-11, 2010)

Non-metal pipes are used in dynamic applications when there is movement between supply and delivery points during service. Dynamic application examples include the use of non-metal pipe risers for offshore loading systems and connections between floating production facilities and subsea equipment. (SRPS EN ISO 13628-11, 2010)

Non-metal pipelines were initially used in benign weather environments. Still, their technological advancement has enabled them to now be used in adverse weather conditions, deeper waters, and higher temperatures. (Bai, 2014).

Non-metal pipelines are primarily used to transport gas, oil, and water in-field over short distances or installed between templates/platforms (Kirkvik H., 2013). Non-metal pipelines are more economically viable than steel pipes. They are light, strong, durable, reliable, corrosion-resistant, and have shorter lead times. They are also quicker, easier, and cheaper to deploy without requiring welding, hot permits, or special pipe-laying barges.

The non-metal pipes consist of many different layers. The main parts are watertight thermoplastics and steel wires that resist corrosion. To obtain resistance to high pressure and good bending ability, the steel wires are twisted helically. To meet requirements, The design of the layers of modular construction is purpose-fit, interactive, and adjustable. The pipes need to be sufficiently non-metal on seabeds that are not level. (Technip, 2015)

Non-metal pipelines have composite structures. The high stiffness of helical steel amour layers provides strength, while polymer sealing layers provide fluid integrity. The maximum number of layers in complex non-metal pipes is 19. The prevention of wear between steel layers or the provision of thermal insulation can be achieved by adding layers. The transferred fluid does not contact the steel wires. As a result, non-metal pipes do not need corrosion resistance. (Technip, 2015).

Polymer sealing layers are combined with helical steel armour layers to produce the composite structure of non-metal pipes. The steel layers provide strength through high stiffness, and the polymer layers provide fluid integrity through low stiffness. Consequently, the pipeline ends up with bending stiffness lower than axial tensile stiffness, allowing its curvature radius to be smaller than that of a homogenous pipe with an equal anti-pressure capacity. The benefits are decreased costs for transport and installation through the storage of long prefabricated spans on reels. (Bai, 2014).

Non-metal pipes are generally designed specifically for each application. However, they can be grouped according to their applications. They can be constructed as either unbonded or bonded.
"The carcass of an unbonded non-metal pipe is an interlocked metallic layer that resists collapse. Internal fluid integrity is provided by an extruded polymer layer, which is the internal pressure sheath. The internal pressure sheath and system internal pressure loads are supported radially by the pressure armour's interlocked metallic layer". (SRPS EN ISO 13628-11, 2010)

The non-metal pipe material that is used in the chosen case study is HDPE. Solid-walled HDPE pipes have been in use since their introduction in the 1960s. The pipe's high abrasion and galvanic corrosion resistance, and resilience to shock, make polyethylene a preferable solution to steel, GRP, or concrete piping.
HDPE pipes are durable, tough, and have a dependable butt fusion system of joining the pipe, supplemented by the availability of a wide array of mechanical fittings. It also allows for the cost-effective installation of long-length pipes (plasticpipe.org).

2.3 Pipe Failure Modes

Besides lateral displacement, there are several other ways in which a subsea pipeline can fail. This section will be giving a brief overview on the other failure modes that a marine pipeline can experience over time.

2.3.1 Buckling

The analysis of all types of buckling requires the use of the nominal wall thickness. The British Standard PD 8010-2:2004 categorizes buckling into the following:

2.3.1.1 Local Buckling

External pressure, axial tension/compression, bending, torsion or a combination of these loads cause the pipe wall to buckle locally. (PD 8010-2, 2004)

2.3.1.2 *Propagation buckling*

After local buckles or localized damage have formed, external pressure can cause propagation buckling. (PD 8010-2, 2004)

2.3.1.3 *Restrained buckling*

Axial compressive forces formed by high heat and pressures produce restrained buckling. This buckling can either result in buried/trenched pipes experiencing vertical upheaval or pipes snaking horizontally. (PD 8010-2, 2004)

2.3.2 ***Fracture***

A fracture can quickly propagate for a long distance on a pipe that contains gas or a volatile liquid. Selecting a material with sufficient toughness against fracture is the main way of controlling fracture. The properties of the chosen material must be able to limit the fracture to a localized leak through fracture arrest. (PD 8010-2, 2004)

2.3.3 ***Vertical displacement***

Bai (2014) states that during soil liquefaction, the relative density of the soil is reduced. The result of this is either the floatation of a buried pipe or further settlement, depending on the pipe's relative density. Liquefaction is caused by excess pore water pressures in the soil structure caused by direct wave action or cyclic loading.

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2.3.4 ***Fatigue***

The effect of fatigue is established by addressing all cyclic stresses caused by pressure, thermal loading, and external loading. The fatigue life of a pipe must be designed to exceed its proposed design life. The fatigue life depends on the number and range of expected stress cycles and the largest possible defect size. (PD 8010-2, 2004)

2.4 Wave Force Interactions with a Pipeline

In the natural environment, quasi-steady currents are caused by the following mechanisms (Schoonees JS, 2020):

- Tides
- Continental circulation
- Storm surges
- Wind stress interactions with wave orbital oscillations resulting in net particle speeds

There are unsteady flow conditions in areas where a pipe experiences oscillatory current that is produced by waves. The forces that act on the pipe are the vertical lift force, drag force and inertia force. (Schoonees JS, 2020):

A vertical lift force is perpendicular to the current due to the differential water velocity between the underside of the pipe and above the pipe, creating a pressure differential. Drag forces are also perpendicular to the pipeline but they are in the horizontal plane. Drag and Inertia forces are added to obtain the Horizontal Force. (Schoonees JS, 2020):

During a wave cycle the velocity and acceleration components are out of phase. Hence, to obtain the calculation is typically done on a time-basis to assess loading through a wave cycle. (Schoonees JS, 2020):

The Morison Equation's Vertical Lift, Drag and Inertia Forces can be estimated as follows (Schoonees JS, 2020):

$$F_L = 0.5\ \rho.C_L D.u^2 \tag{1}$$

$$F_D = 0.5\ \rho.C_D D.u^2 \tag{2}$$

$$F_M = (\pi\ \rho.C_M\, D^2/u)\ du/dt \tag{3}$$

2.5 Methods of Calculating Displacement

Internal pressure and increased temperature produce a compressive axial force, which can increase lateral displacement. Heavy pipes resist hydrodynamic loads from the biggest waves. Slightly lighter pipes experience some displacement but do not move a considerable distance. Instead, they move into depressions, accumulating passive soil resistance, and there is no displacement increase over time. Lighter pipes move out of their depression regularly, and the displacement is assumed to be proportional with time (Marineman, 2015).

There are three approaches to on-bottom stability: (Marineman, 2015)

- Ensure absolute stability: based on force equilibrium and ensures that soil resistance is more than the hydrodynamic loads.
- Ensure no break-out: allows small displacement. The maximum displacement must not exceed half of the pipe diameter to obtain virtual stability and to prevent pipe movement outside its cavity. During small movements, passive resistance build-up is maximized. Consequently, there is no accumulated displacement, and the maximum displacement depends on time. Cavities are partially formed by fast velocity variations which reduce vapour pressure.
- Allow accumulated displacement: specify larger allowable displacements. The pipe breaks out of its cavity with proportionally calculated displacement with time.

This section will be discussing eight methods that can be used to determine pipe displacement. These methods include the Force Balance Method, the Scandinavian Design, the Simplified Stability Analysis, Generalized Stability Analysis and Dynamic Analysis in the DNV-RP-E305 code and the Absolute Lateral Static Stability Method, Generalized Lateral Stability Method and Dynamic Lateral Stability Analysis in the DNV-RP-F109 code.

However, due to the exclusion of Finite Element analysis and Dynamic Modelling from the scope of this study, there is limited information provided on the two Dynamic Analysis methods. Their sections entail brief overviews on the methods while more detailis are provided on the rest of the methods.

2.5.1 *Force Balance Method*

A subsea pipeline is considered stable if it has sufficient submerged weight for the lateral soil resistance to be high enough to restrain the pipe from deflecting sideways. Although the empirical or calibrated methods, which are discussed in sections 2.5.3 and 2.5.4 below, have widely replaced this method, it is still common when a pipeline is exposed to pure current (Chukwu O.D. et al., 2016).

Cumming G et al., (2009) noted that the Force Balance Method defined in DNV-OS-F101 (2000) was not included in the revised DNV-OS-F101 (2007).

The force balance calculation forming the basis for the static stability approach is:

$$\gamma_s * F_H \leq \mu(W_s - F_L) \tag{4}$$

γ_s is a safety factor typically taken as 1.1, F_H is the horizontal hydrodynamic load, W_s is the pipeline submerged weight, F_L is the vertical lift force, and μ is the Coulomb friction factor.

The traditional design approach for submarine pipelines expressed in the early design codes required no horizontal movement during a pipe's exposure to environmental conditions associated with an extreme return period (Cumming G et al., 2009).

2.5.2 Scandinavian Design

Pos, Russel, and Zwamborn (1986) state that the temperature of the effluent determines the material of the pipe (HDPE or Polypropylene). Therefore, the maximum internal pressure stress is dependent on service life, material, temperature, and sufficient buckling safety from loads. In addition, the thickness of the pipe wall must be enough to prevent the maximum internal pressure from being exceeded.

The allowance of pipe movement is limited to an annually or bi-annually event. The pipeline is assumed to be resting on anchor blocks and clear of the seabed. During the sinkage of anchor blocks, pipe clearances are increased by the lift force. Pipe buoyancy occurs during the exceedance of anchor weight by the lift force. This occurs until vertical forces find a new equilibrium and clearance is established again. The deposition of sand under the pipe is limited by increasing water velocity and turbulence. (Pos, Russel and Zwamborn,1986).

2.5.2.1 Scandinavian Design Procedure (CSIR, 1985) :

1. Choose the type of material (HDPE or PP) by using the temperature of the effluent.
2. Calculate the required thickness for the wall of the pipe.
3. Assume that the friction factor is 1.

   Requirement for stability against sliding:

   $$(W - F_L) > F_H \tag{5}$$

   Since the pipe is off the bed:

   $$F_L = 0 \tag{6}$$

   Thus, it follows:

   $$W \geq F_H \tag{7}$$

4. Calculate the forces on the pipe by using maximum wave heights
5. The anchor blocks usually protrude more than D/4 from the pipe.
6. For more reliable results in shallow water and local wave condition, use a higher-order wave theory. Assume a minimum clearance of D/4 before horizontal motion.
7. Select anchor block spacing that will ensure the permissible bending is not exceeded.
8. Pipe movement is expected to be annually or bi-annually. Therefore, the pipe forces must be determined by using the once-a-year occurring maximum wave height.
9. Assume that the pipe will always be clear of the bottom due to resting on anchor blocks protruding more than D/4 from the pipe. If local scour causes the anchor blocks to sink into the seabed, a lift force would develop, which increases at smaller pipe clearances. The pipe becomes buoyant when the lift force exceeds the anchor weight. This continues until the vertical forces find a new equilibrium which re-establishes a clearance. Increased water velocity and turbulence prevents sand from being deposited beneath the pipe.
10. Pipe force calculations may be obtained by using a high-order wave theory in shallow water and local wave conditions or wave conditions converted by refraction diagrams to the site, while accounting for conditions limited by depth. The Morison equation is then fed by this information.

11. The Scandinavian Design Procedure calculates the wave forces on a pipe by using the Morison equations. Namely:

$$F_{H\ TOTAL} = F_{H\ inertial} + F_{H\ drag} \tag{8}$$

where:

$$F_{H\ inertial} = C_M * M_{disp} * \acute{\upsilon} * \sin\alpha \tag{9}$$

$$F_{H\ drag} = C_D * \tfrac{1}{2}\rho * D\ U * \sin\alpha\ \left|U * \sin\alpha\right| \tag{10}$$

$$F_L = C_L * \tfrac{1}{2}\rho * D * (U * \sin\alpha)^2 \tag{11}$$

12. The spacing between anchor blocks must be sufficient for ensuring that the permissible bending stress will not be exceeded.

2.5.2.2 Calculation of Anchor Block Weights

The Scandinavian Design Procedure requires the weighting along a pipeline to be equivalent to the maximum horizontal 1:1 year wave force expected at that position.

2.5.3 DNV-RP-E305

The primary basis of DNV-RP-E305 is the results of the Pipeline Stability Project (PIPESTAB) carried out by SINTEF (1983 – 1987). Providing information on the stability of pipes used to design submarine pipelines is the primary goal. The design method is relevant only for seabed-resting pipes or pipes before stabilization. Therefore, the pipe's stability relies on environmental forces, soil resistance, and the pipe's submerged weight (Marineman, 2015).

The following conditions affect on-bottom stability design: pipe data, bathymetry, topographical conditions of the seabed, location of pipe restraints, environmental conditions, and the geotechnical conditions of the seabed (Marineman, 2015).

The following definitions of the pipeline are used (Marineman, 2015):

- Zone 1: Seabed location is more than 500m from the platform/subsea template.
- Zone 2: Seabed location is up to 500m from the platform/outfall/subsea template.

The following factors determine the allowable lateral displacement (Marineman, 2015).:

- State laws
- Presence of Seabed obstacles
- Width of corridor
- Distance to the platform/restraint.

Half of the width of a pipe corridor must not be exceeded by the allowable lateral displacement. Hence, the pipe must not move beyond the corridor. (Marineman, 2015).

When there is insufficient information, the allowable maximum lateral displacement may be assumed as: (Marineman, 2015).:

Zone 1 – 20m

Zone 2 – 0m

“In zone 2, the allowable lateral displacement may be greater than 0 if the pipeline and the supporting structure can acceptably accommodate the effect of displacement”. However, no information is detailed in the DNV-RP-E309 on what happens if a pipe is moved during a single storm event and is subject to a second storm event (Marineman, 2015).

Chukwu O.D. et al., (2016) state that the DNV-RP-E305 code does not guide forces interacting between the pipe and seabed on carbonate soils. It makes no allowance for pipe embedment or soil resistance, and hydrodynamic loading. As a result, the effects of seabed stability are not considered within the pipeline's response during storm loading. The DNV-RP-E305 is not relevant for pipes having external diameters smaller than 0.406m, nor for regions strongly dominated by current.

The DNV-RP-305 has the following analysis methods:

- Simplified Stability Analysis
- Generalized Stability Analysis
- Dynamic Analysis

Calibrated methods should be conservative when they are not within the areas where they are applicable. The DNV-RP-E305’s Simplified and Generalised Methods are only relevant for pipes with an external diameter larger than 0.406m. Furthermore, vital current-dominated regions are relevant. (Cumming G. et al., 2009).

2.5.3.1 *Simplified Stability Analysis*

This analysis is used for stability calculations where the required submerged weight is a priority. It is based on simplified models and the quasi-static balancing of forces that act on the pipe. Generalized stability analysis results are used to calibrate the simplified stability analysis. The design curves in the Generalised Method are replaced by a quasi-static method. 20m is the maximum lateral displacement in the Simplified Method (Cumming G. et al., 2009).

This method is suitable for checking stability in all normal design situations by using a calibration factor F_w. Stability in the quasi-static method is given by the following expression (Bai, 2014):

$$(W_s / F_w - F_L) * \mu \geq F_D + F_I \tag{12}$$

Then, W_s can be figured out by:

$$W_s = ((F_D + F_I + \mu F_L) / \mu)_{max} * F_w \tag{13}$$

2.5.3.2 Generalized Stability Analysis

The Generalized Stability Analysis is used in preliminary design calculations and detailed design calculations and in pipe sections where movement and strain are essential. The results from the dynamic analysis are generalized through non-dimensional parameters and for end conditions. Major assumptions made are rough pipe; no initial embedment; no load history previously; inclusion of passive soil resistance due to partial pipe penetration into the soil under cycle loading; hydrodynamic forces modified for wake effects; pipe penetration does not reduce hydrodynamic forces; medium sand soil and JONSWAP wave spectrum.

These are the requirements for this method to be applicable:

- $D \geq 0.4m$
- $4 \leq K \leq 40$
- $0 < M < 0.8$
- $0.05 < S < 8$ (for clay soil)
- $0.7 < G < 1$ (for sand soil)

The Generalized method consists of the following set of design response curves developed based on many dynamic FE simulations, using the PONDUS FE stability software (Marineman, 2015):

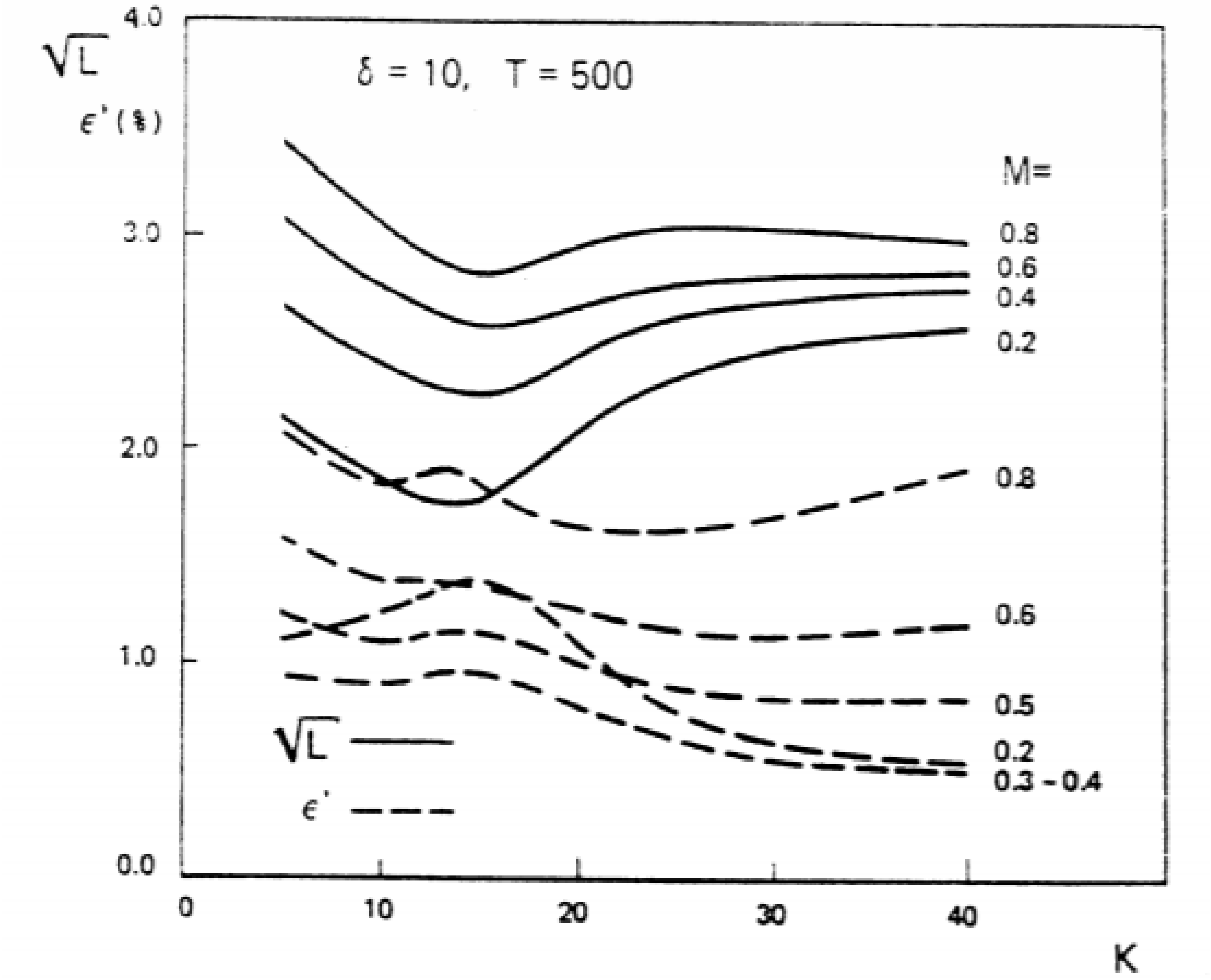

Figure 2-1: The corresponding Generalized Weight Parameter L and Bending Strain versus K of M values (Marineman, 2015)

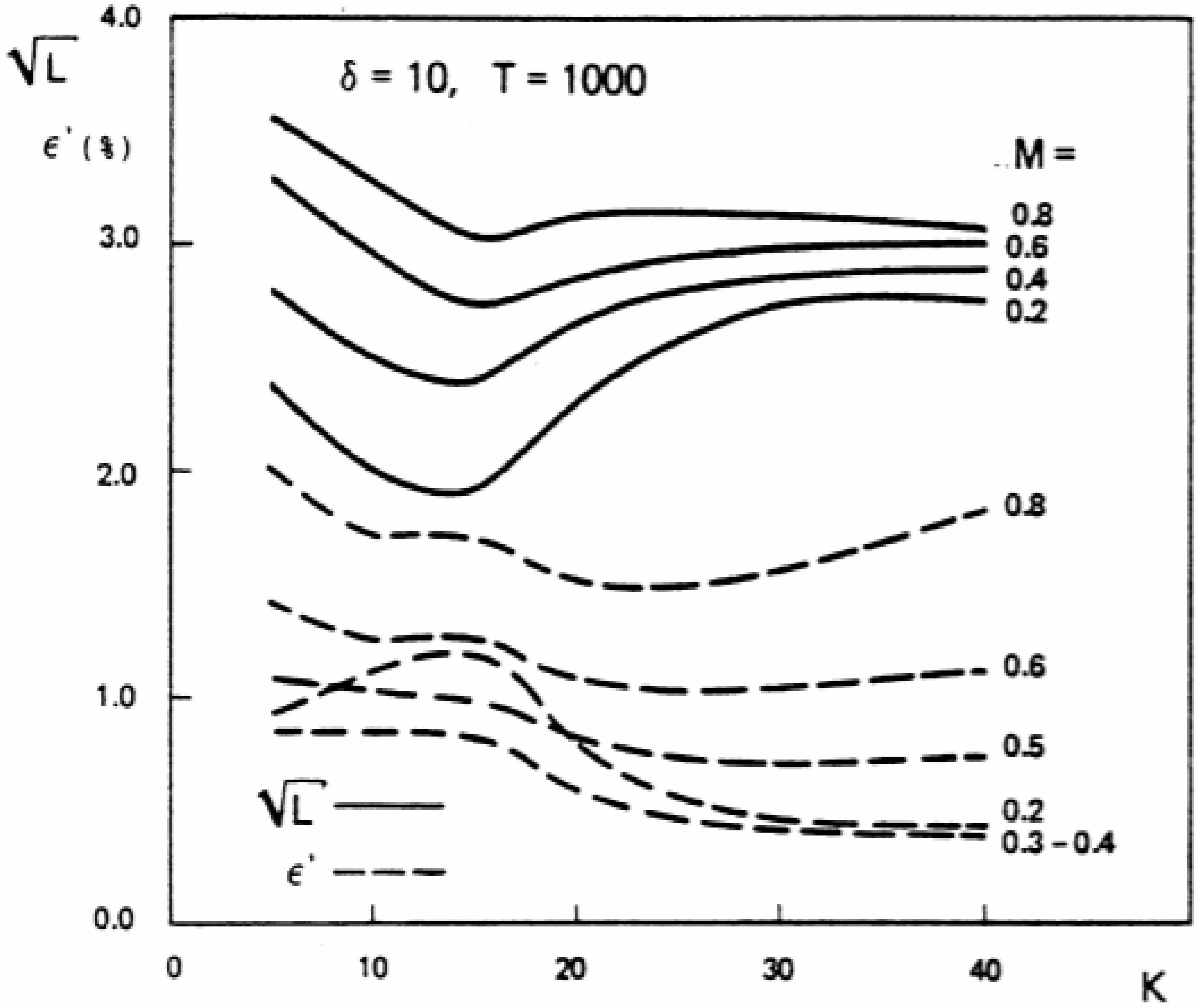

Figure 2-2: L and ϵ' vs. K of M values when δ = 10 and T = 1000 (Marineman, 2015)

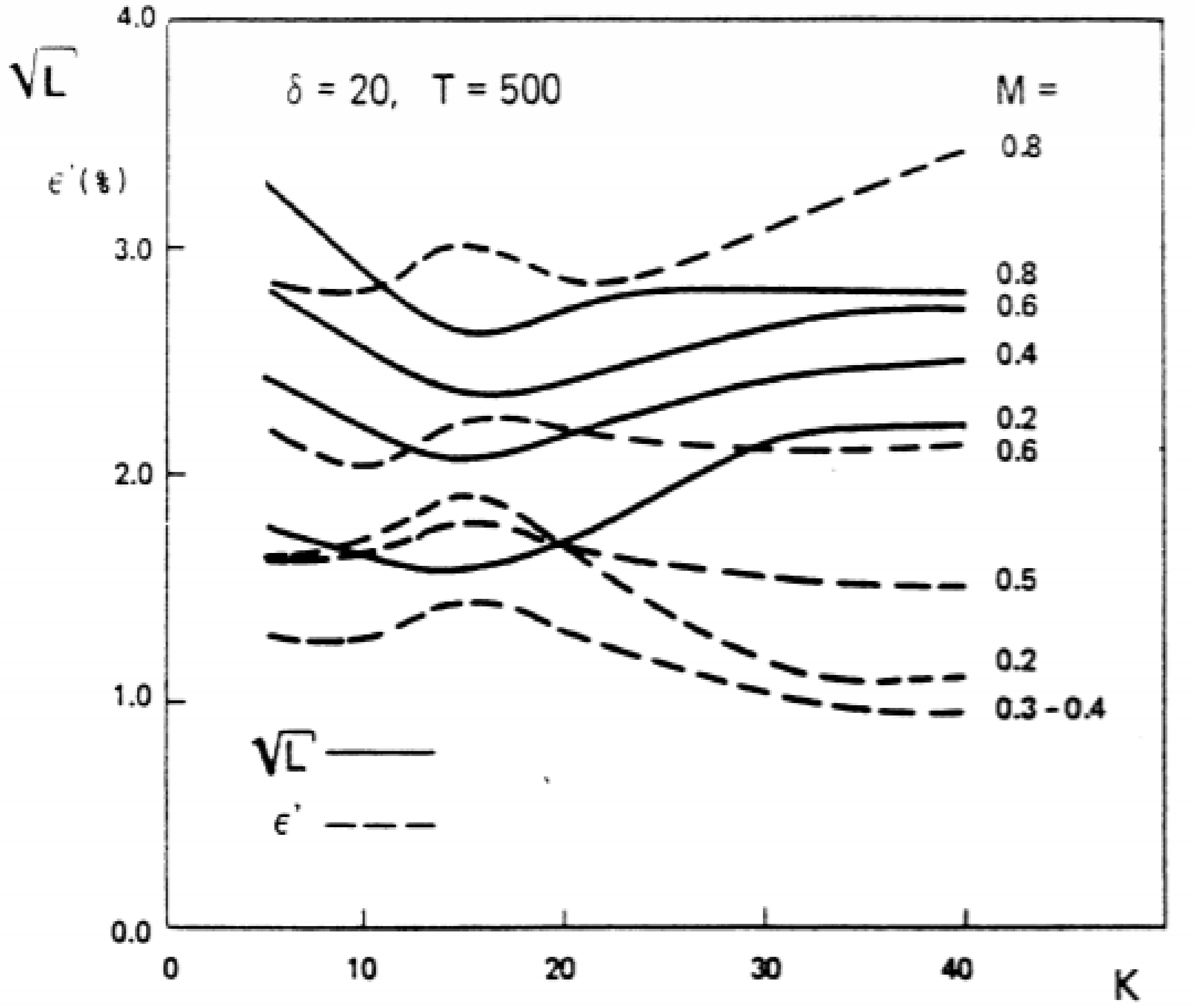

Figure 2-3: L and ϵ' vs. K of M values when δ = 20 and T = 500 (Marineman, 2015)

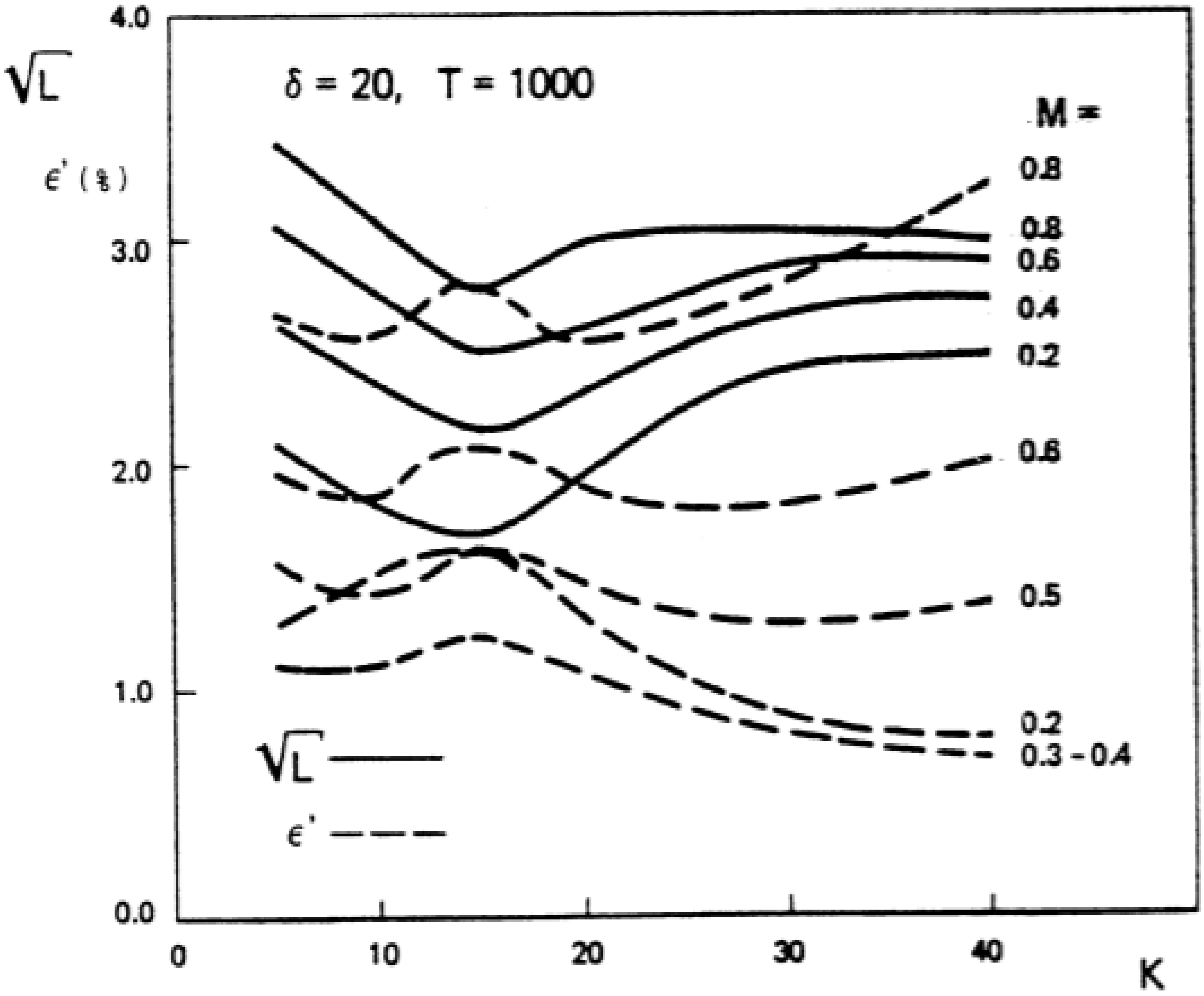

Figure 2-4: L and ϵ' vs. K of M values when δ = 20 and T = 1000 (Marineman, 2015)

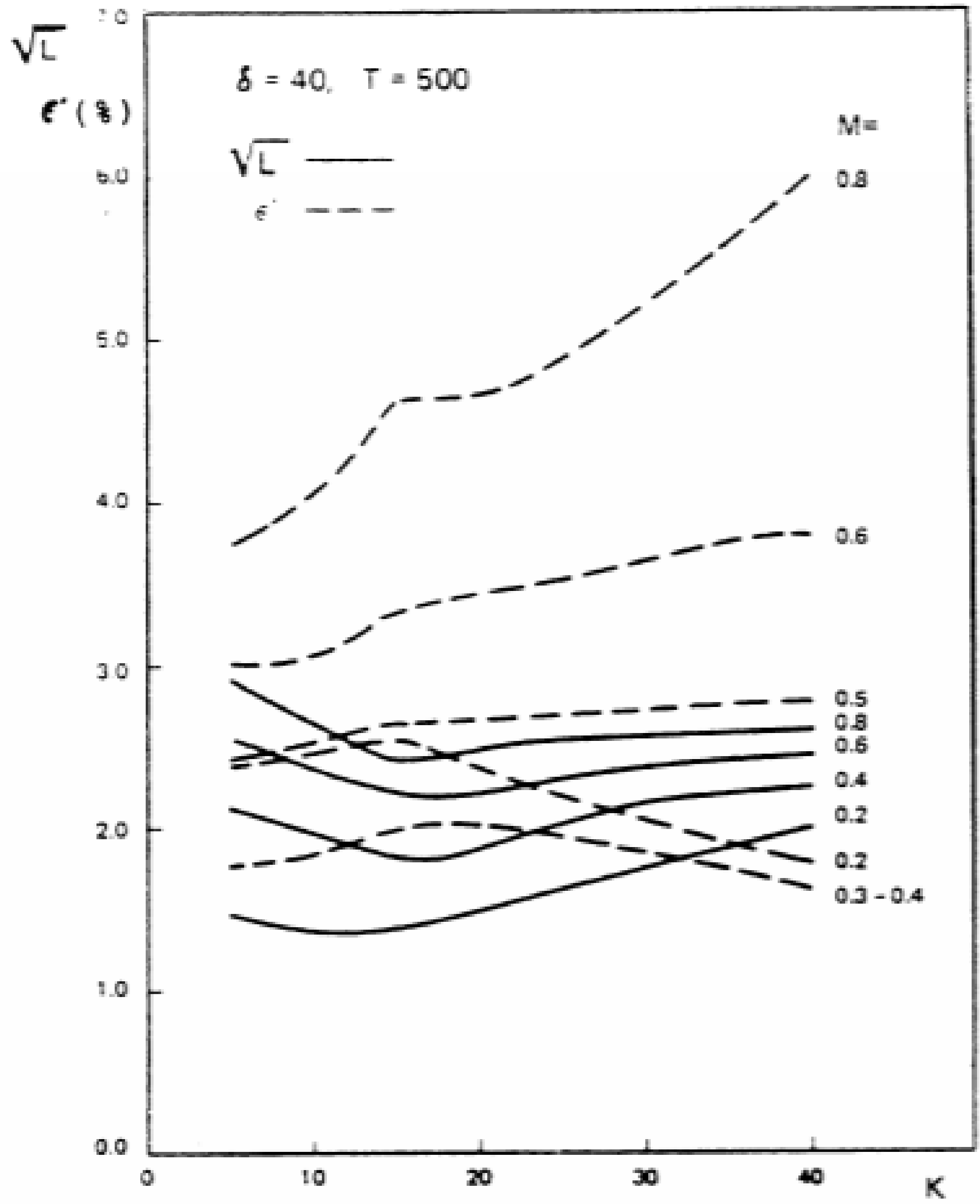

Figure 2-5: L and ϵ' vs. K of M values when δ = 40 and T = 500 (Marineman, 2015)

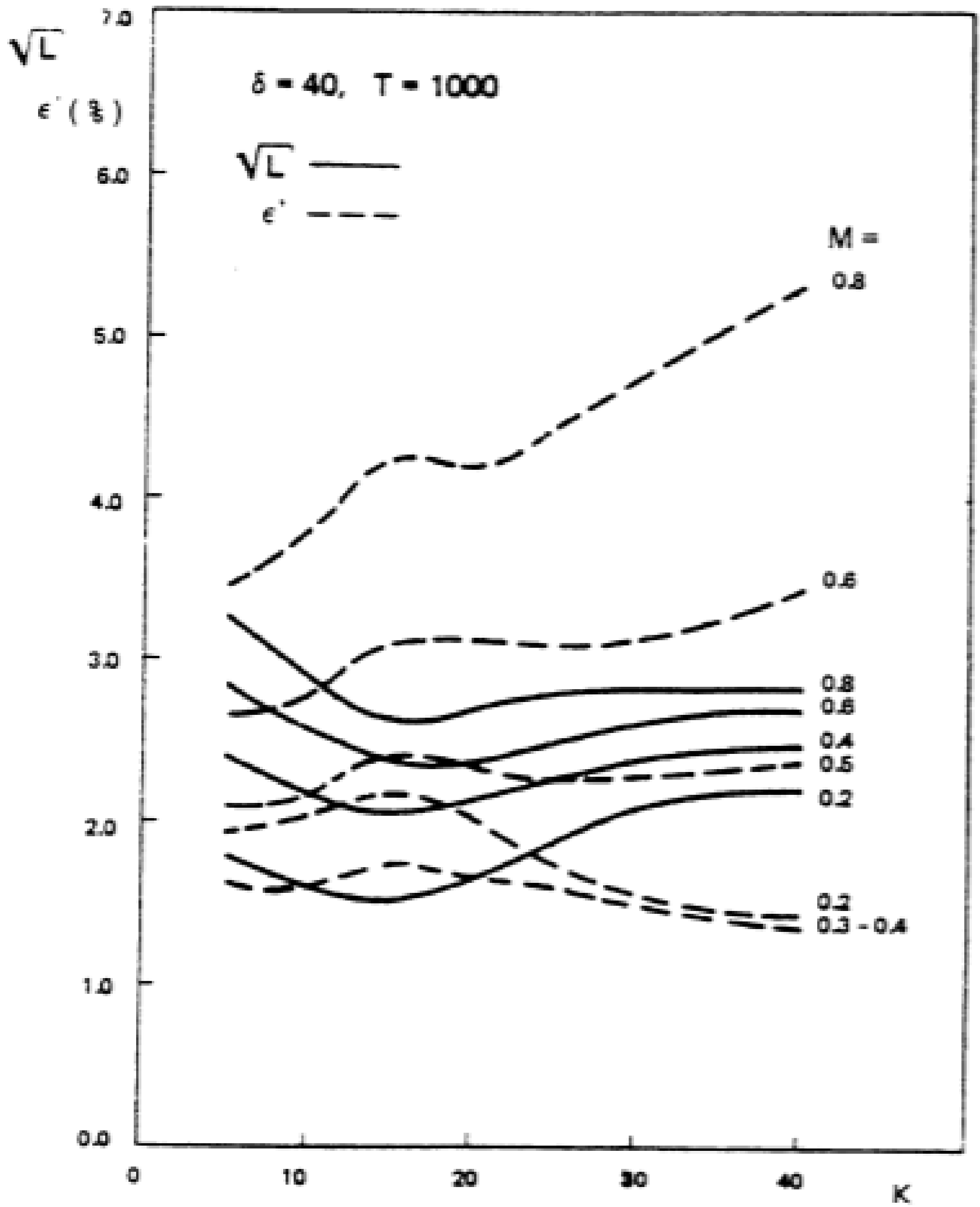

Figure 2-6: L and ϵ' vs. K of M values when δ = 40 and T = 1000 (Marineman, 2015)

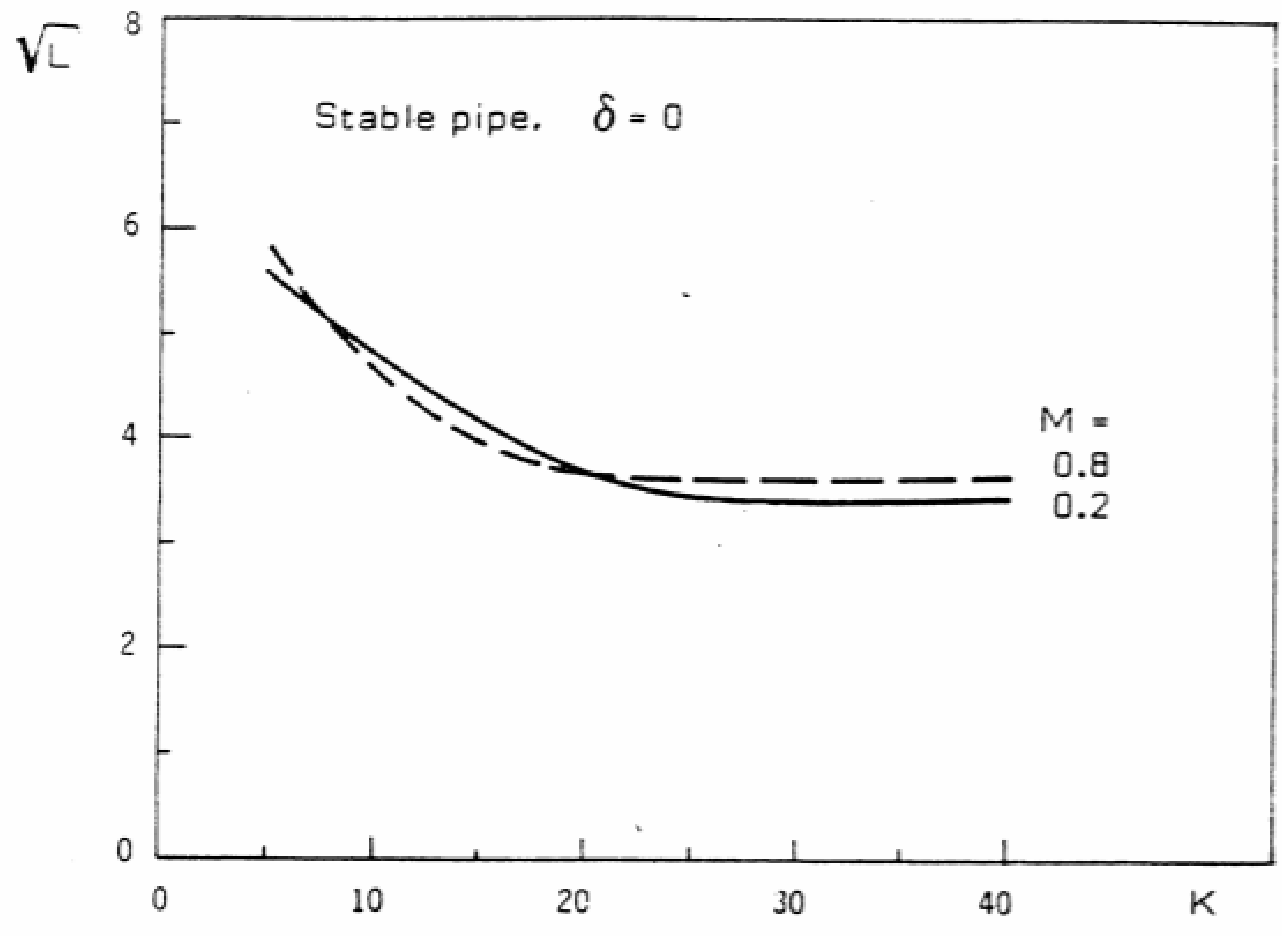

Figure 2-7: A stable pipe's Generalized Weight Parameter L (δ = 0). (Marineman, 2015)

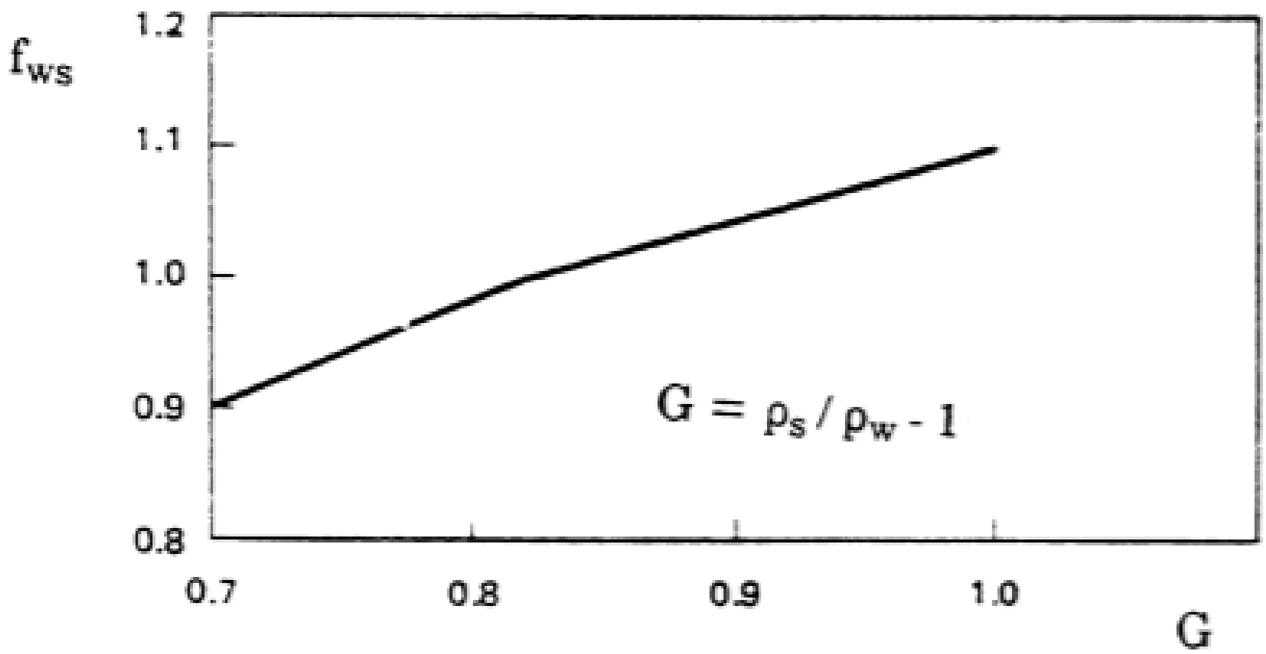

Figure 2-8: f_{ws} vs. Soil Density, G (Marineman, 2015)

Figure 2-1 to Figure 2-6 “give the generalized weight parameter L, versus K for specific M values, solid lines. Figures are given for values of the scaled lateral pipe displacement, δ = Y/D, of 10, 20 and 40 and based on sea states with 500 and 1000 wave periods, i.e., T = T1/Tu = 500,1000. The bending strain in the pipe at a fixed point along the pipeline section is also found” in the figures. Figure 2-7 is “also given the generalized weight parameter L for a complete stable pipe (8 = 0) on sand soil.”

The non-dimensional parameters are calculated as follows:

$K = U_s\ T_u / D$ (14)

$L = W_s / 0.5\ \rho_w\ D\ U^2{}_s$ (15)

$M = U_c / U_s$ (16)

$G = (\rho_s – \rho_w) / \rho_w = \rho_s / \rho_w – 1$ (17)

$S = W_s / (D\ S_u)$ (18)

$T = T_1 / T_u$ (19)

The design curves were developed by systematic simulations using the dynamic analysis. The results of many simulations were used to derive the curves so that more cumbersome dynamic analysis does not have to be done. (Cumming G. et al., 2009)

2.5.3.3 Dynamic Analysis

A pipe section is dynamically simulated under the influence of waves and currents. This analysis is a time-domain solution for the non-linear behaviour of pipes and incorporates 3-Dimensional effects, surface wave spectra, and non-linear soil resistance. Dynamic Finite Element simulations are the basis of a set of design response curves. It involves modelling hydrodynamic forces, soil resistance, dynamic response, restraints, the seabed's current velocity, pipe structural behaviour, wave spectrum, and corresponding time series and boundary conditions (Chukwu O.D et al., 2016).

Different pipe lengths must be analysed to determine the sensitivity of results to ensure sufficient pipe length is modelled. Critical strain response requires the modelling of the non-linear stress/strain behaviour of pipe material. The effect of pipe-soil friction and resistance from the penetration of the pipe into the soil must be used for modelling soil resistance (Chukwu O.D et al., 2016).

The dynamic analysis has the following uses:

- When high-level detail on the response of the pipe is required
- For the re-analysis of a critical existing pipeline
- For critical areas needing detailed analysis (e.g., Pipe crossings, risings).

2.5.4 DNV-RP-F109

The DNV-RP-F109 supports and complies with DNV Offshore Standard "Submarine Pipeline Systems"; DNV-OS-F101, 2000 and supplements relevant National Rules Regulations. The target safety levels in DNV-OS-F101 consider lateral displacements made excessive by hydrodynamic loads as a serviceability limit state (SLS) (Marineman, 2015).

The updated DNV-RP-F109 makes no allowance for the effects of pipe embedment. Uneven levels of embedment are not considered, and no provision is made for quantitatively guiding carbonate soils.

The design methods for lateral on-bottom stability are as follows:

- Dynamic Lateral Stability Analysis
- A Generalized Lateral Stability Method
- Absolute Lateral Static Stability Method.

2.5.4.1 *Absolute Lateral Static Stability Method*

This method is based on the static equilibrium of forces ensuring that the pipe experiences no lateral displacement under maximum hydrodynamic loads during sea state. The Absolute Lateral Static Stability Method is based on a Load Resistance Factor Design (LRFD) approach with additional partial safety factors which satisfy the target safety level in F101 (2007). The relatively high partial safety factors range from 1.32 to 1.64 for safety class Normal. (Bai, 2014)

Cumming G et al (2009) state that it appears that the Absolute Lateral Static Method was intended to replace the Force Balance Method and Simplified Stability Analysis.

The design wave approach used by this method calculates the required pipe submerged weight, ensuring no lateral displacement for a selected single maximum wave. This method assumes that bending stiffness has no effect on the required submerged weight for absolute stability (Chukwu O.D. et al., 2016).

The requirement for absolute stability can be relevant for pipe spools, pipes on narrow supports, cases dominated by the current, and stiff clay. A pipeline can be considered statically stable if the following requirements are satisfied (Bai, 2014):

$$\gamma_{sc} * \frac{F^*{}_Y + \mu F_Z^*}{\mu * w_s + F_R} \leq 1 \tag{20}$$

and

$$\gamma_{sc} * \frac{F_Z^*}{w_s} \leq 1 \tag{21}$$

γ_{sc} = safety factor

$F^*{}_Y$= peak horizontal load, = $r_{tot,Y}$ * 0.5 * ρ_w * D * C^*_Y * $(U^* + V^*)^2$ (22)

F_Z^* = peak vertical load, = $r_{tot,z}$ * 0.5 * ρ_w * D * C^*_Z * $(U^* + V^*)^2$ (23)

This relates to the equations of the Force Balance Method and Simplified Stability Analysis of the DNV-RP-E305.

It is suggested that for conditions dominated by waves, the requirement of no displacement will lead to the requirement for a very heavy pipeline. “The no-displacement requirement may be relevant for stability, e.g., pipe spools, pipes on narrow supports, in stiff clay and current-dominant cases. (Cumming G. et al., 2009).

The coefficients of friction and passive resistance due to initial penetration can be used to calculate pipe soil interaction. In the calculation of initial penetration, it can be assumed that the lift force is zero and that the pipe weight is at its maximum prior to the design sea state. (DNV-RP-F109, 2017)

The following equation may be used if the resistance is accounted for by only friction (DNV-RP-F109, 2017):

$$L^* = C^*_y / \mu + C^*_z \tag{24}$$

This is plotted in the following figures below for μ = 0.6 and μ = 0.2 respectively. The value of 2 is used for K_u for plotting purposes:

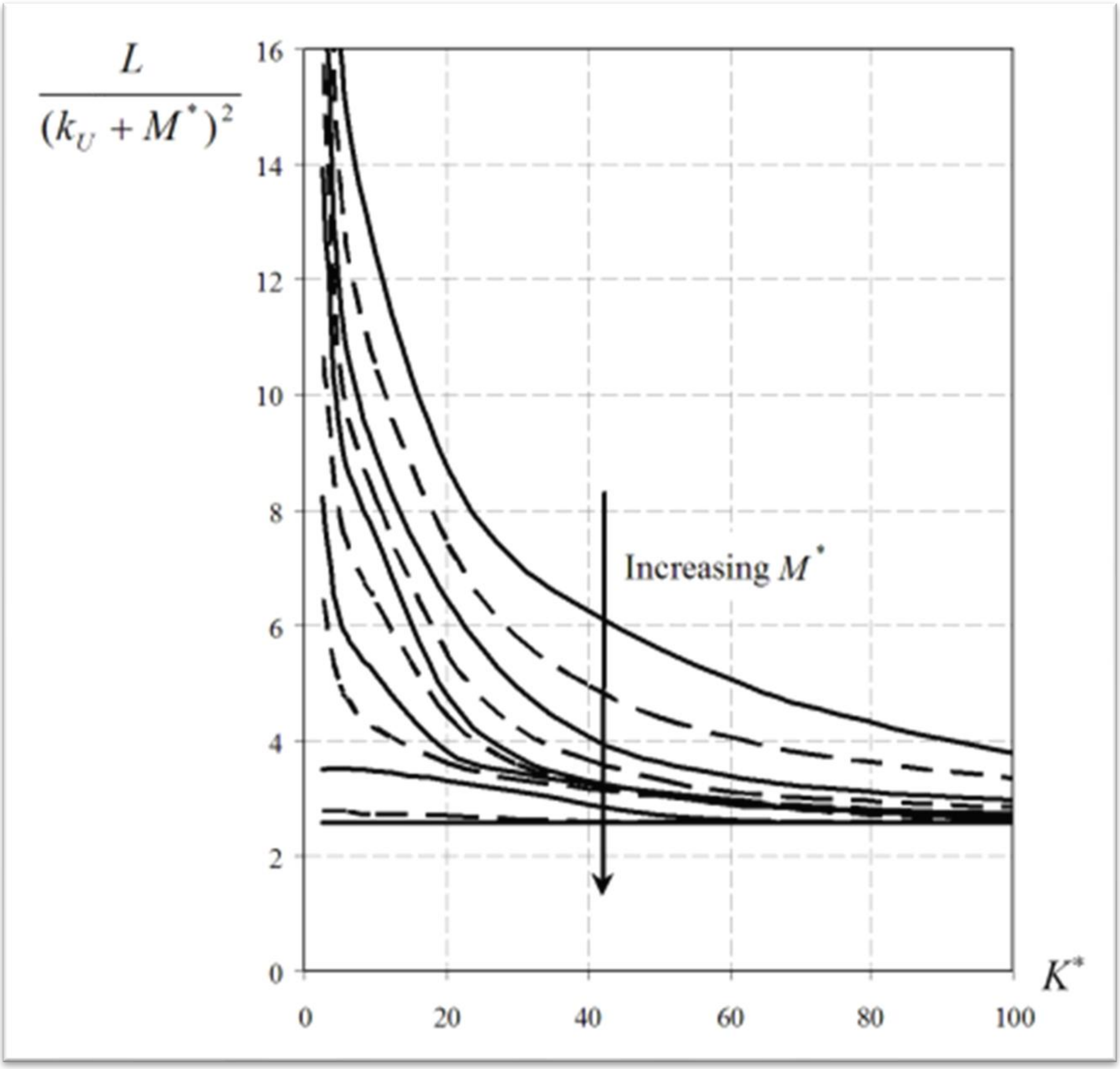

Figure 2-9: Required weight for μ = 0.6 and F_R = 0 (DNV-RP-F109)

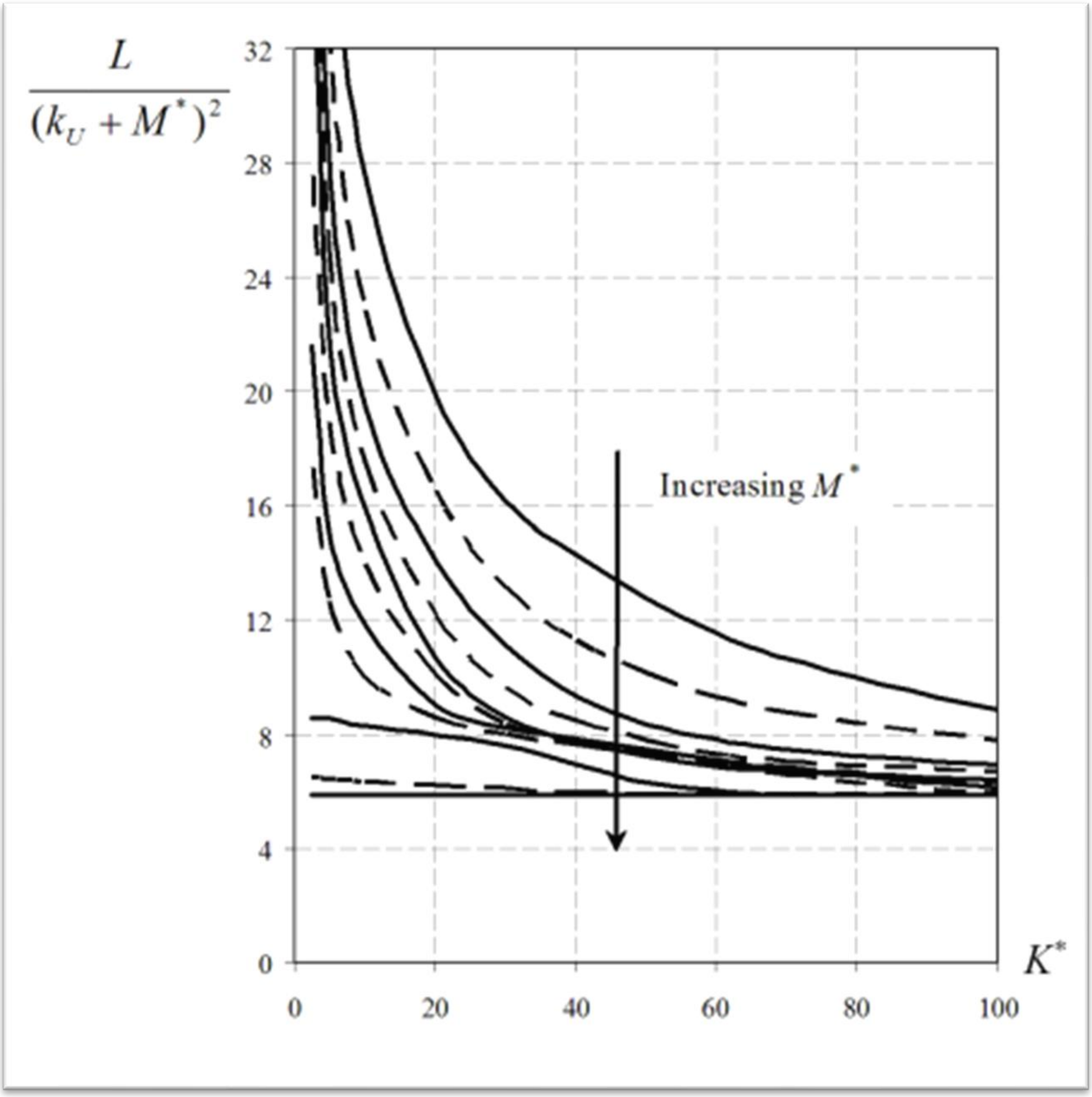

Figure 2-10: Required weight for μ = 0.2 and F_R = 0 (DNV-RP-F109)

2.5.4.2 *Generalized Lateral Stability Method*

The Generalised Lateral Stability Method was first introduced in DNV-RP-E305. It has been maintained in the new DNV-RP-F109, but it has been significantly revised and updated. There is no longer a stated limitation on the method's validity in terms of pipeline diameter or on the current to wave ratios, i.e., the parameter space for which the Generalised Method is applicable appears to have been expanded. In contrast to the E305 (1988), which presented design curves for lateral displacement ranging from 0 to 40 times the pipe's external diameter, the new design code is based on a lateral displacement limited to 10 pipe diameters during the given sea state (Marineman, 2015).

The Generalized Stability Analysis is used in preliminary design calculations and detailed design calculations and in pipe sections where movement and strain are essential. The results from the dynamic analysis are generalized through non-dimensional parameters and for end conditions. Major assumptions made are rough pipe; no initial embedment; no load history previously; inclusion of passive soil resistance due to partial pipe penetration into the soil under cycle loading; hydrodynamic forces modified for wake effects; pipe penetration does not reduce hydrodynamic forces; medium sand soil and JONSWAP wave spectrum.

The following are applied in the generalized method (Bai, 2014):

- A virtually stable pipe on sand
- A virtually stable pipe on clay
- Ten pipe diameter displacement on sand
- Ten pipe diameter displacement on clay.

The recommendation is limiting lateral displacements to 10 pipe diameters in temporary conditions and during operation when other limit states are not investigated (e.g., fatigue and maximum bending). The minimum submerged weight of a pipe is determined by a design curve method. (Bai, 2014).

There are design curves for on-bottom stability design with an allowed lateral displacement that ranges from less than 0.5D (virtually stable pipes) to 10D during a given sea state. L_{stable} is the weight required for a pipe to obtain virtual stability and L_{10} is the weight required for a pipe to obtain a 10D displacement. (DNVGL-RP-F109, 2017)

Numerous one-dimensional dynamic analyses were used to obtain the curves. This method should not be used for soils with $s_g < 1.05$.

This design approach is applicable to $N \leq 0.024$ for clay and $N \leq 0.048$ for sand. The curves are valid for $G_c \leq 2.78$ only. Absolute stability can be used for higher values of Gc.

The minimum pipe weight required to obtain a virtually stable pipe can be found from the following design points independent of N:

Table 2-1: Minimum weight, $L_{stable} / (2 + M)^2$, for pipe on sand, $K \geq 10$ (DNV-RP-F109)

K M	10	15	20	30	40	≥ 60
≤ 0.2	1.50	1.42	1.35	1.25	1.22	1.22
0.4	1.82	1.70	1.61	1.53	1.50	1.50
0.5	2.19	1.97	1.83	1.69	1.61	1.61
0.6	2.65	2.55	2.18	1.99	1.85	1.72
0.8	3.05	2.55	2.32	2.13	2.01	1.90
1.0	3.05	2.55	2.40	2.20	2.06	1.95
1.5	2.65	2.45	2.36	2.24	2.11	2.09
2.0	2.50	2.40	2.35	2.27	2.22	2.19
4.0	2.45	2.40	2.39	2.37	2.37	2.37
≥ 10	2.50	2.50	2.50	2.50	2.50	2.50

For $K \leq 5$, the required weight depends more on N. The following design points can be used for the minimum pipe weight required for obtaining a virtually stable pipe.

Table 2-2: Minimum weight, $L_{stable} / (2 + M)^2$, for pipe on sand, $K \leq 5$ (DNV-RP-F109)

M \ N	0.003	0.006	0.012	0.024	0.048
≤ 0.2	1.55	1.45	1.34	1.24	1.13
0.4	2.00	1.65	1.34	1.24	1.13
0.5	3.30	2.60	1.91	1.24	1.13
0.6	3.75	3.07	2.38	1.70	1.13
0.8	4.00	3.45	2.90	2.36	1.81
1.0	3.90	3.50	3.10	2.71	2.31
1.5	3.25	3.13	3.00	2.88	2.75
2.0	2.75	2.75	2.75	2.75	2.75
4.0	2.60	2.60	2.60	2.60	2.60
≥ 10	2.50	2.50	2.50	2.50	2.50

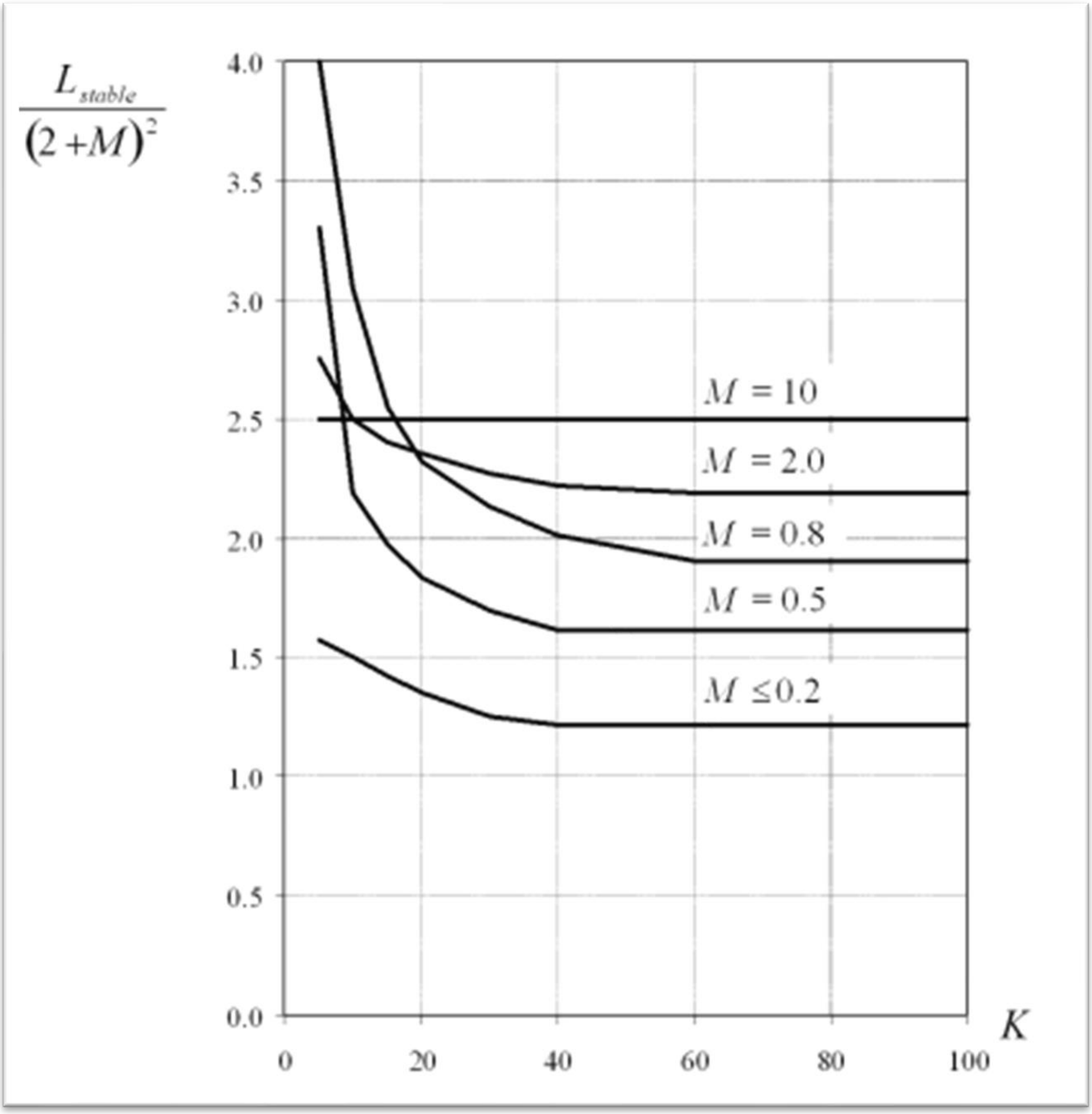

Figure 2-11: Minimum weight, L_{stable} / $(2+M)^2$, for pipe on sand (DNV-RP-F109, 2017)

The minimum pipe weight required to limit the lateral displacement to 10D for pipes on sand can be found from the following design points:

Table 2-3: Minimum weight, L_{10} / $(2 + M)^2$, for pipe on sand (DNV-RP-F109)

K M	= 5	10	15	20	30	40	60	≥ 60
≤ 0.2	0.20	0.41	0.61	0.81	0.69	0.69	0.69	0.69
0.4	0.31	0.62	0.93	0.81	0.75	0.72	0.70	0.70
0.5	0.34	0.69	1.03	0.93	0.83	0.78	0.75	1.00
0.6	0.79	1.20	1.13	1.10	1.07	1.05	1.03	1.02
0.8	0.85	1.40	1.37	1.35	1.33	1.33	1.32	1.31
1.0	1.60	1.50	1.47	1.45	1.43	1.43	1.42	1.41
1.5	1.80	1.70	1.67	1.65	1.63	1.63	1.62	1.61
2.0	1.90	1.80	1.77	1.75	1.73	1.73	1.72	1.71
4.0	2.10	2.00	1.97	1.95	1.93	1.93	1.92	1.91
≥ 10	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50

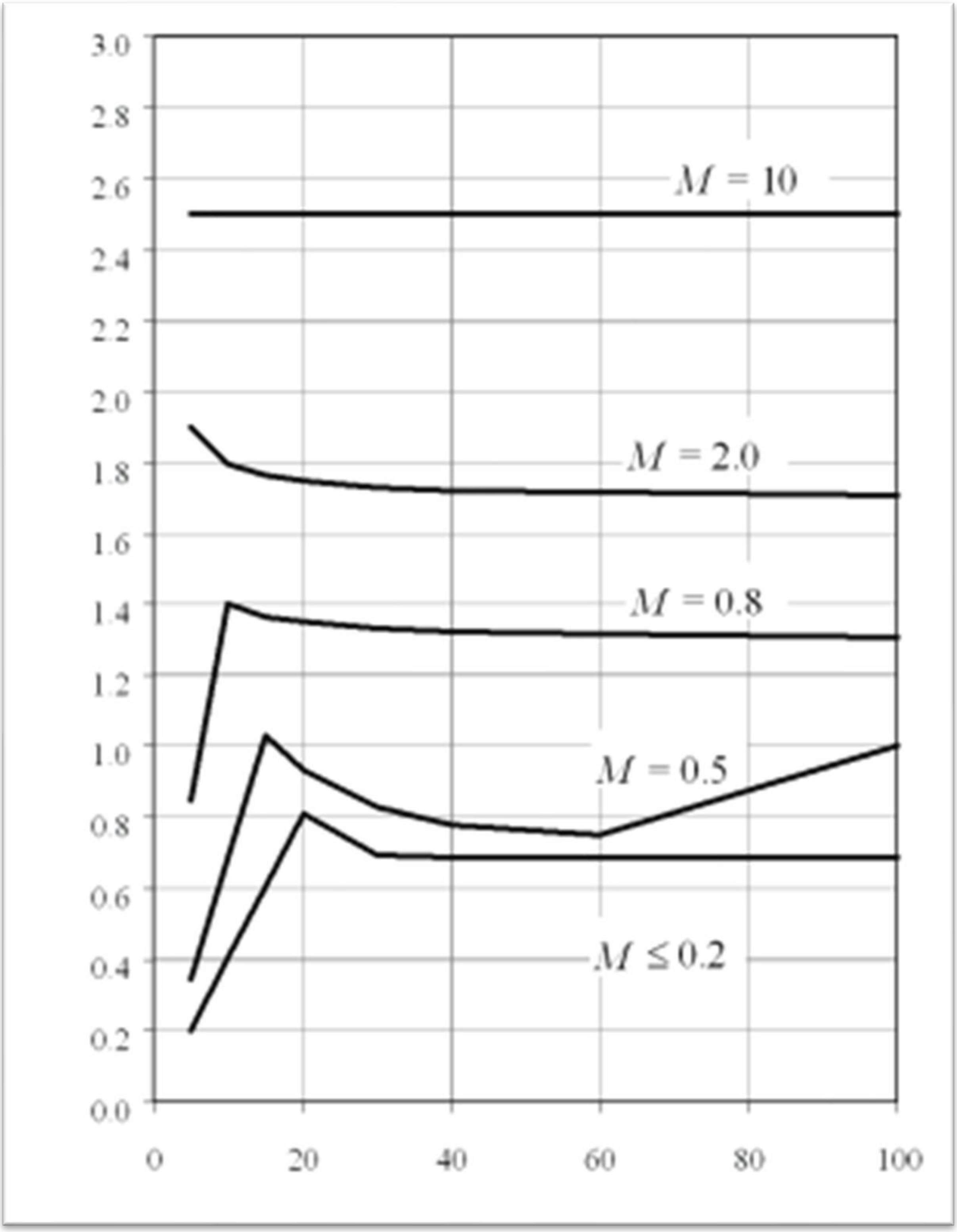

Figure 2-12: Minimum weight, L_{10} / $(2+M)^2$, for pipe on sand (DNV-RP-F109, 2017)

The stability curves for clay are as follows:

Table 2-4: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$ for pipe on clay, Gc = 0.0556 (DNV-RP-F109)

$G_c = 0.0556$								
M	$N \leq 0.003$				$0.006 \leq N \leq 0.024$			
	C_1	C_2	C_3	K_b	C_1	C_2	C_3	K_b
≤ 0.2	0	9	0.6	10	0.2	5	0.5	15
0.4	0	8	0.6	10	0.2	5	0.5	15
0.5	0.1	7	0.6	10	0.4	4	0.5	15
0.6	0.1	7	0.6	10	0.4	4	0.5	15
0.8	0.1	7	0.6	10	0.7	3	0.5	15
1.0	0.4	5	0.6	5	0.7	3	0.5	15
1.5	0.4	5	0.6	5	1.1	2	0.5	15
2.0	0.7	3	0.6	5	1.6	0	0.5	15
≥ 4.0	1.4	1	0.6	5	1.9	0	0.5	15

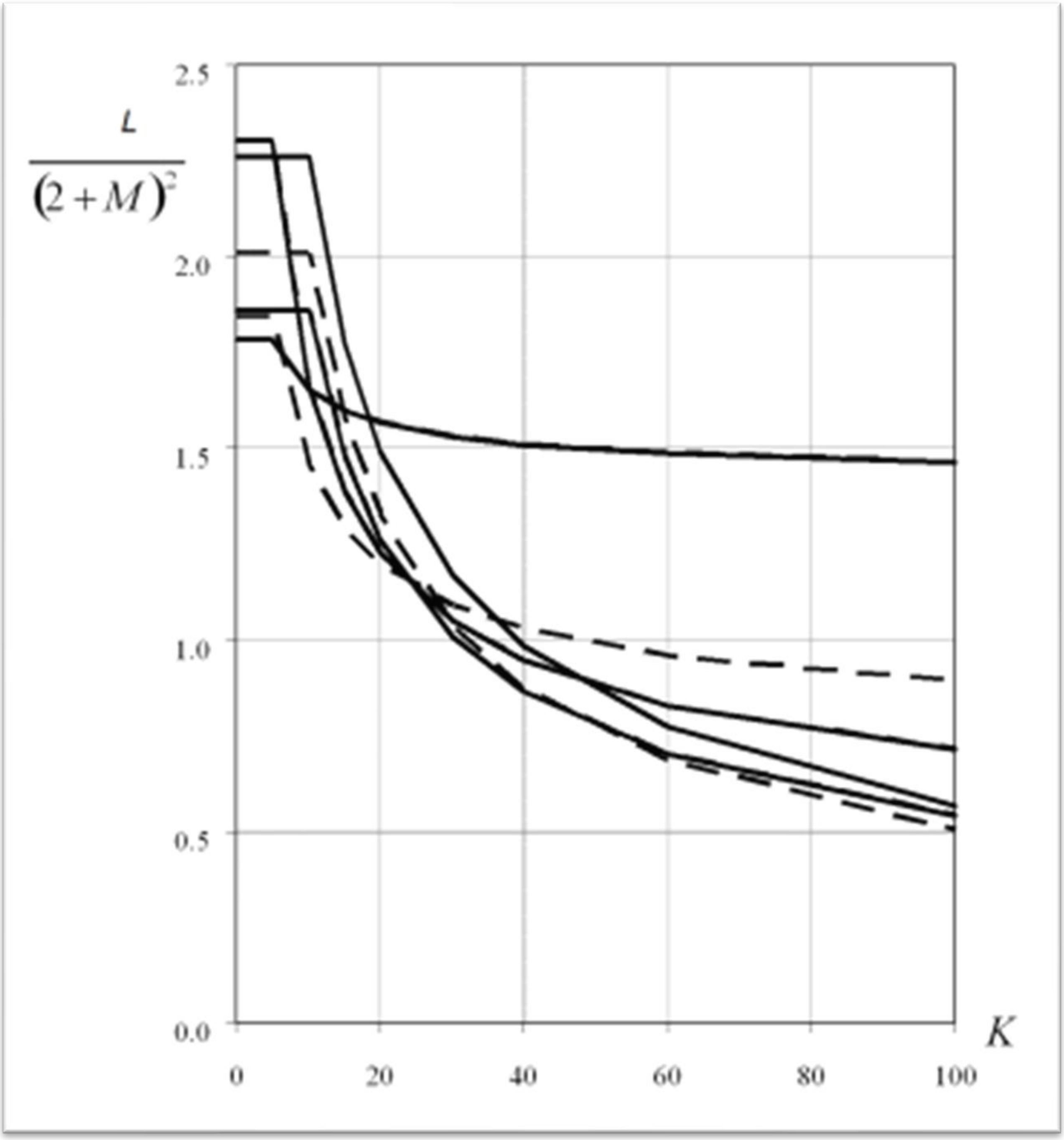

Figure 2-13: Minimum weight for a pipe on clay, Y = 10.τ / 1000, N ≤ 0.003, Gc = 0.0556 (DNV-RP-F109, 2017)

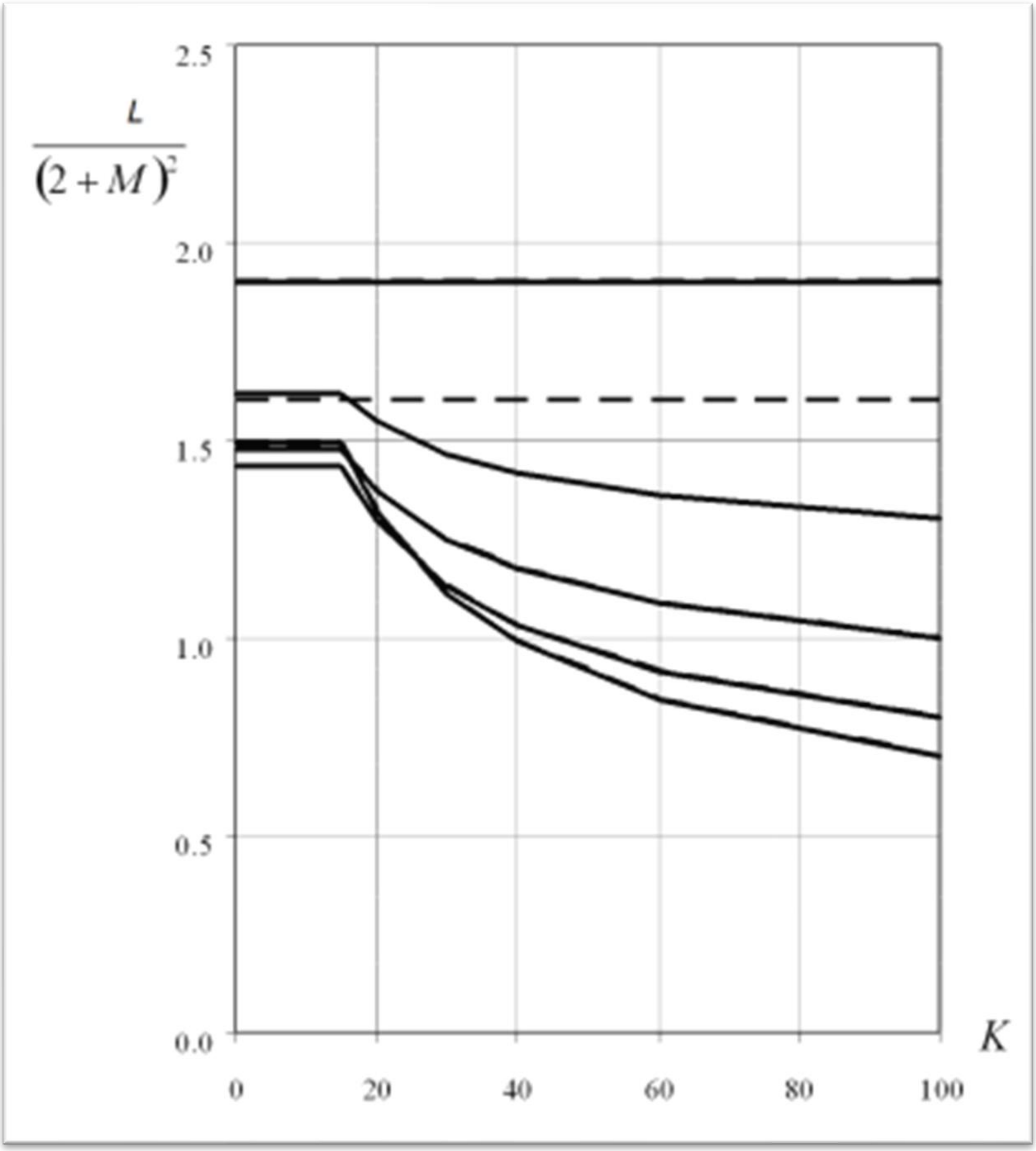

Figure 2-14: Minimum weight for a pipe on clay, Y = 10.τ / 1000, 0.006 ≤ N ≤ 0.003, Gc = 0.0556 (DNV-RP-F109, 2017)

Table 2-5: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, Gc = 0.111 (DNV-RP-F109)

$G_c = 0.111$								
M	$N \leq 0.003$				$0.006 \leq N \leq 0.024$			
	C_1	C_2	C_3	K_b	C_1	C_2	C_3	K_b
≤ 0.2	0.1	9	0.6	10	0.1	7	0.6	10
0.4	0.1	8	0.6	10	0.1	7	0.6	10
0.5	0.1	8	0.6	10	0.1	7	0.6	10
0.6	0.1	8	0.6	10	0.2	6	0.6	10
0.8	0.4	7	0.6	5	0.3	6	0.6	10
1.0	0.4	7	0.6	5	0.4	6	0.6	10
1.5	0.4	5	0.6	5	0.8	4	0.6	10
2.0	0.7	3	0.6	5	1.5	0	0.6	10
≥ 4.0	1.4	1	0.6	5	1.5	0	0.6	10

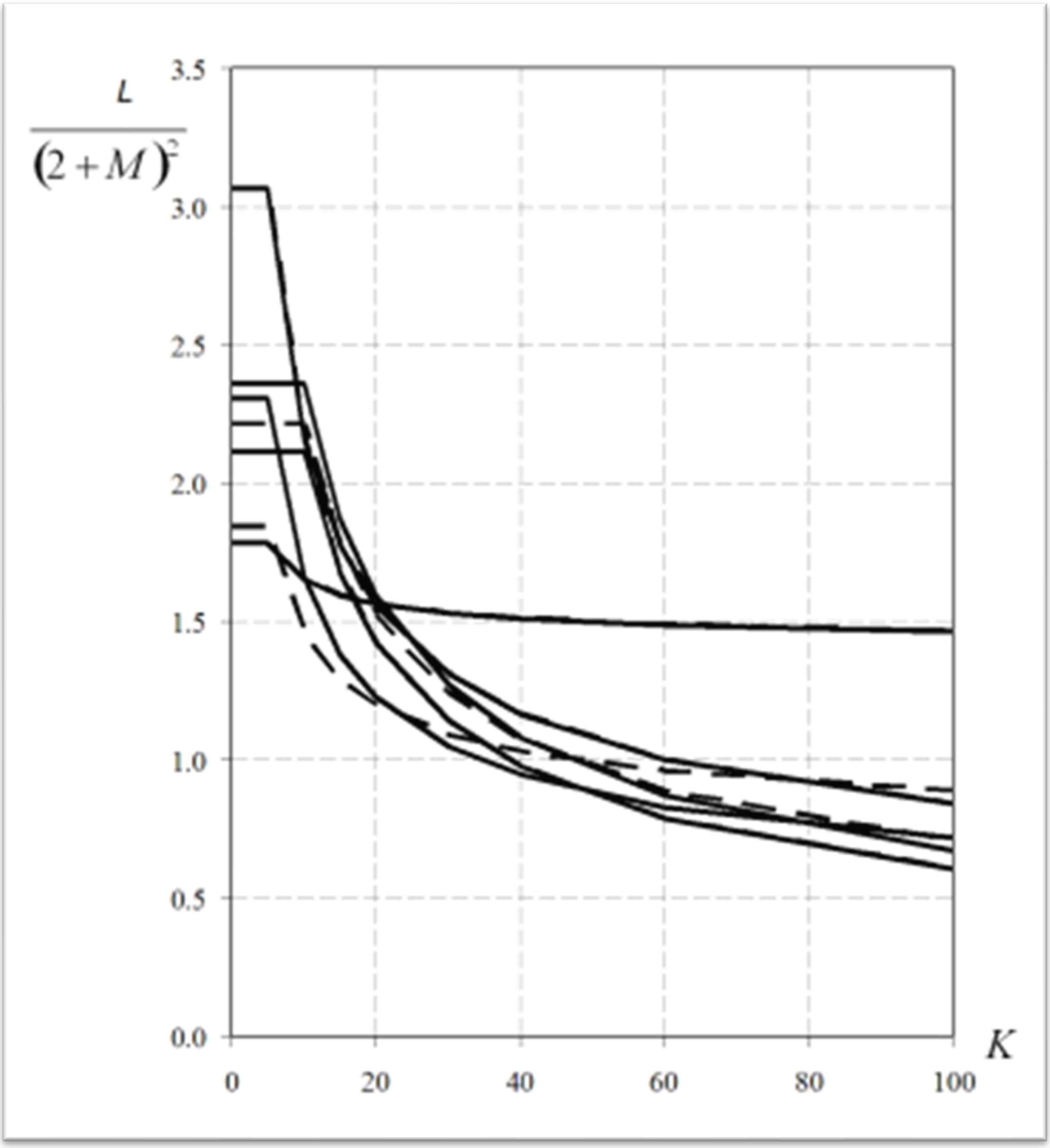

Figure 2-15: Minimum weight for a pipe on clay, Y = 10.τ / 1000, N ≤ 0.003, Gc = 0.0111 (DNV-RP-F109, 2017)

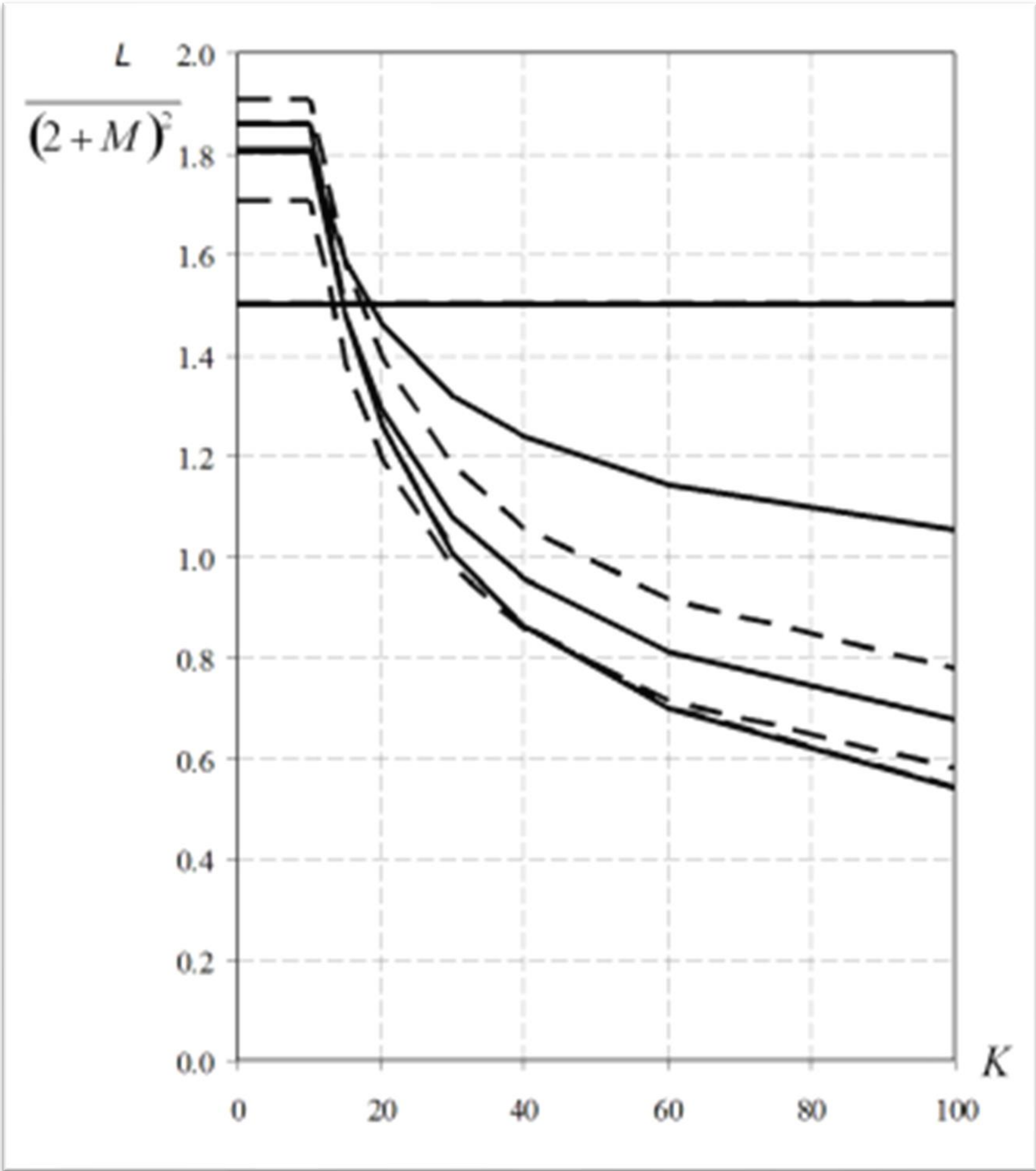

Figure 2-16: Minimum weight for a pipe on clay, Y = 10.т / 1000, 0.006 ≤ N ≤ 0.024, Gc = 0.111 (DNV-RP-F109, 2017)

Table 2-6: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, $G_c = 0.222$ (DNV-RP-F109)

$G_c = 0.222$								
M	$N \le 0.003$				$0.006 \le N \le 0.024$			
	C_1	C_2	C_3	K_b	C_1	C_2	C_3	K_b
≤ 0.2	0.1	8	0.5	15	0.1	8	0.5	10
0.4	0.1	7	0.5	10	-0.3	8	0.5	10
0.5	0.1	7	0.5	10	-0.1	7	0.5	10
0.6	0.1	7	0.5	10	0.0	7	0.5	10
0.8	0.1	7	0.5	5	0.1	6	0.5	5
1.0	0.1	7	0.5	5	0.1	6	0.5	5
1.5	0.1	7	0.5	5	0.5	3	0.5	5
2.0	0.1	7	0.5	5	0.9	2	0.5	5
4.0	0.1	7	0.5	5	1.7	0	0.5	5
≥ 10	0.1	7	0.5	5	1.7	0	0.5	5

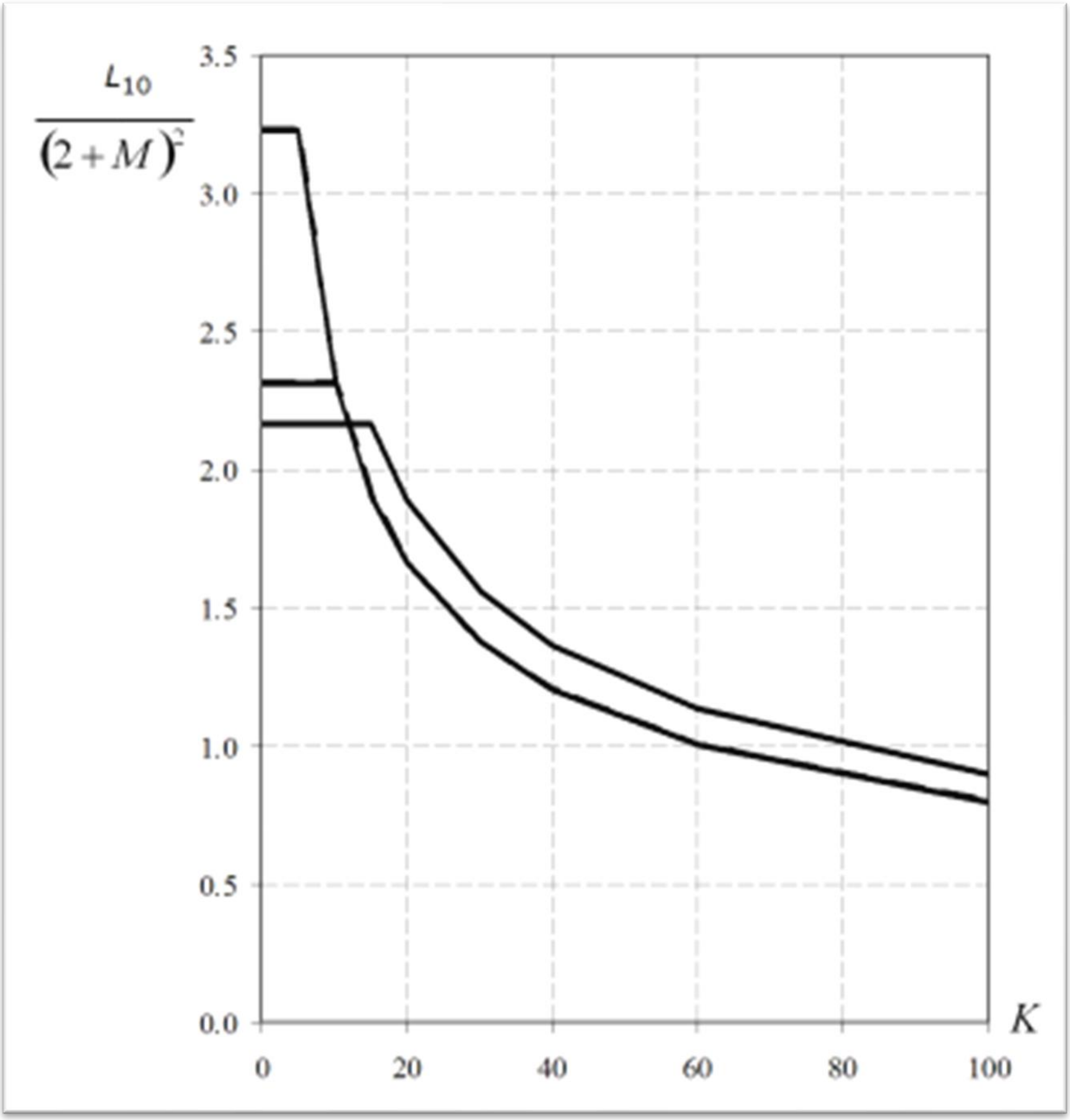

Figure 2-17: Minimum weight for a pipe on clay, Y = 10.т / 1000, N ≤ 0.003, Gc = 0.222 (DNV-RP-F109, 2017)

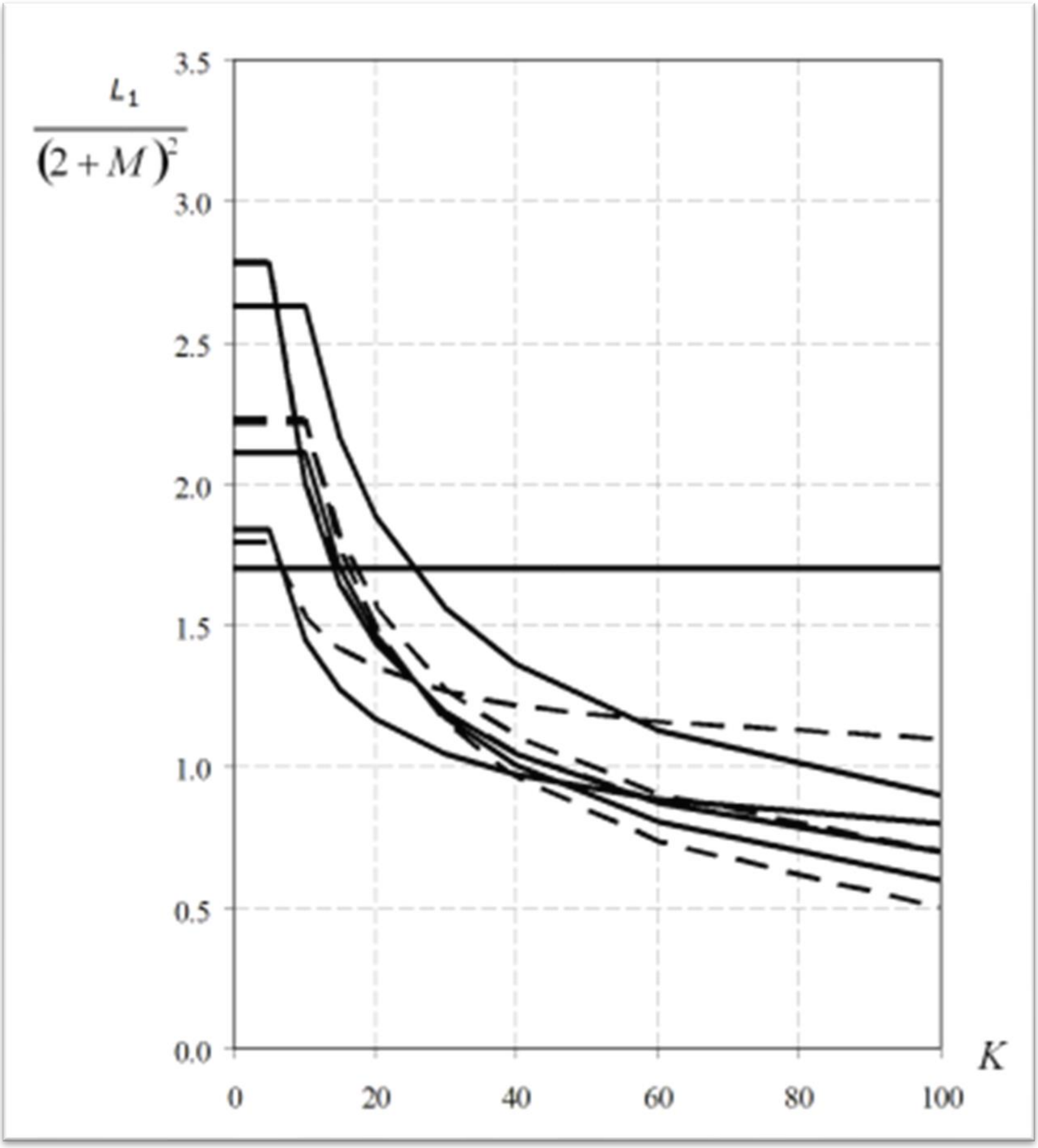

Figure 2-18: Minimum weight for a pipe on clay, Y = 10.τ / 1000, 0.006 ≤ N ≤ 0.024, Gc = 0.222 (DNV-RP-F109, 2017)

Table 2-7: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, G_c = 0.556 (DNV-RP-F109)

G_c = 0.556								
M	$N \leq 0.003$				$0.006 \leq N \leq 0.024$			
	C_1	C_2	C_3	K_b	C_1	C_2	C_3	K_b
≤ 0.2	1.4	3	0.5	15	0.0	8	0.5	10
0.4	0.5	6	0.5	5	0.3	6	0.5	5
0.5	0.5	6	0.5	5	0.3	6	0.5	5
0.6	0.5	6	0.5	5	0.3	6	0.5	5
0.8	1.1	4	0.5	5	0.4	7	0.5	5
1.0	1.3	4	0.5	10	0.4	7	0.5	5
1.5	1.2	7	0.5	10	0.8	6	0.5	10
2.0	1.2	7	0.5	10	0.8	6	0.5	10
4.0	1.2	7	0.5	10	0.8	6	0.5	10
≥ 10	1.4	6	0.5	10	0.8	6	0.5	10

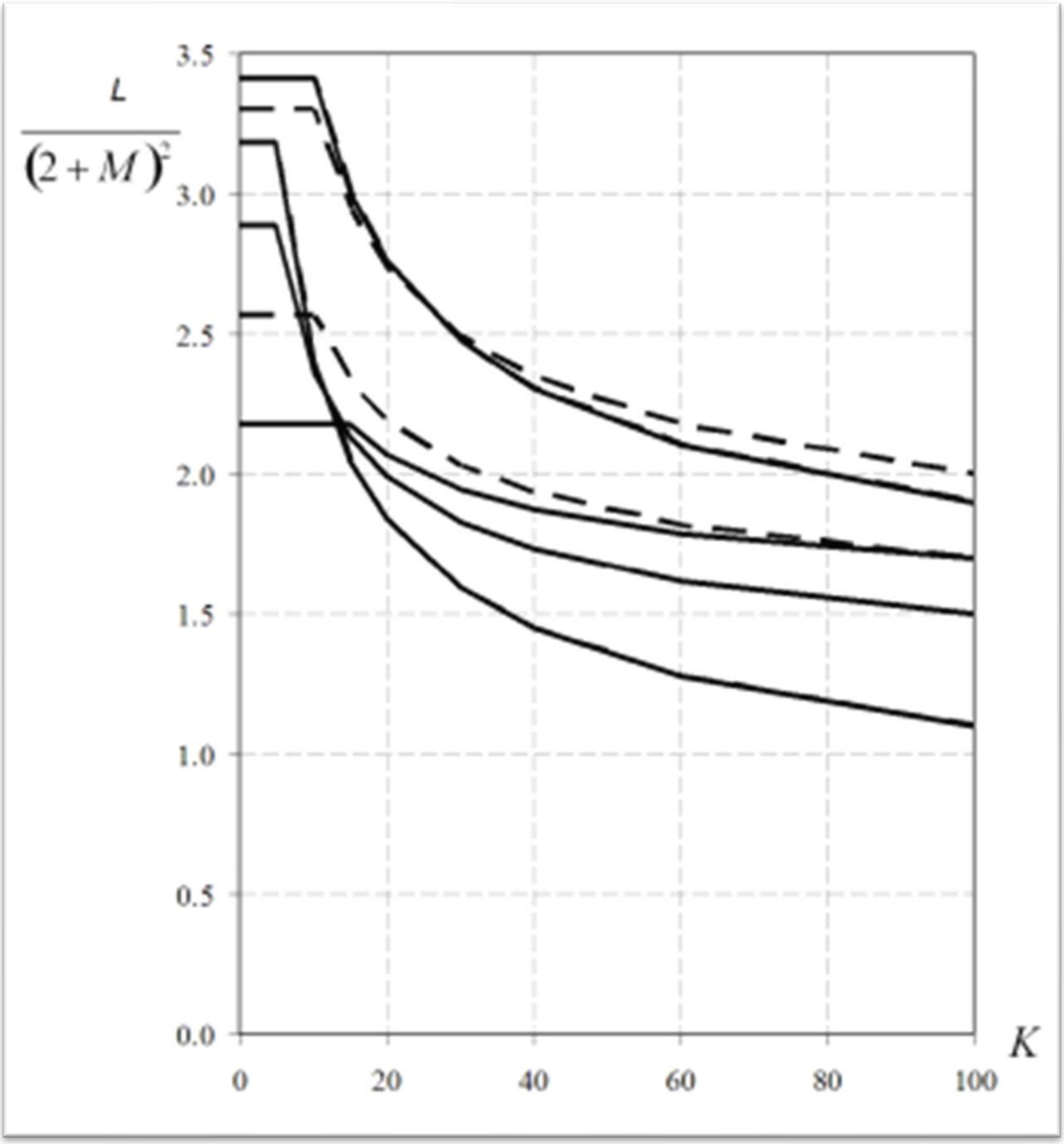

Figure 2-19:Minimum weight for a pipe on clay, Y = 10.τ / 1000, N ≤ 0.003, Gc = 0.556 (DNV-RP-F109, 2017)

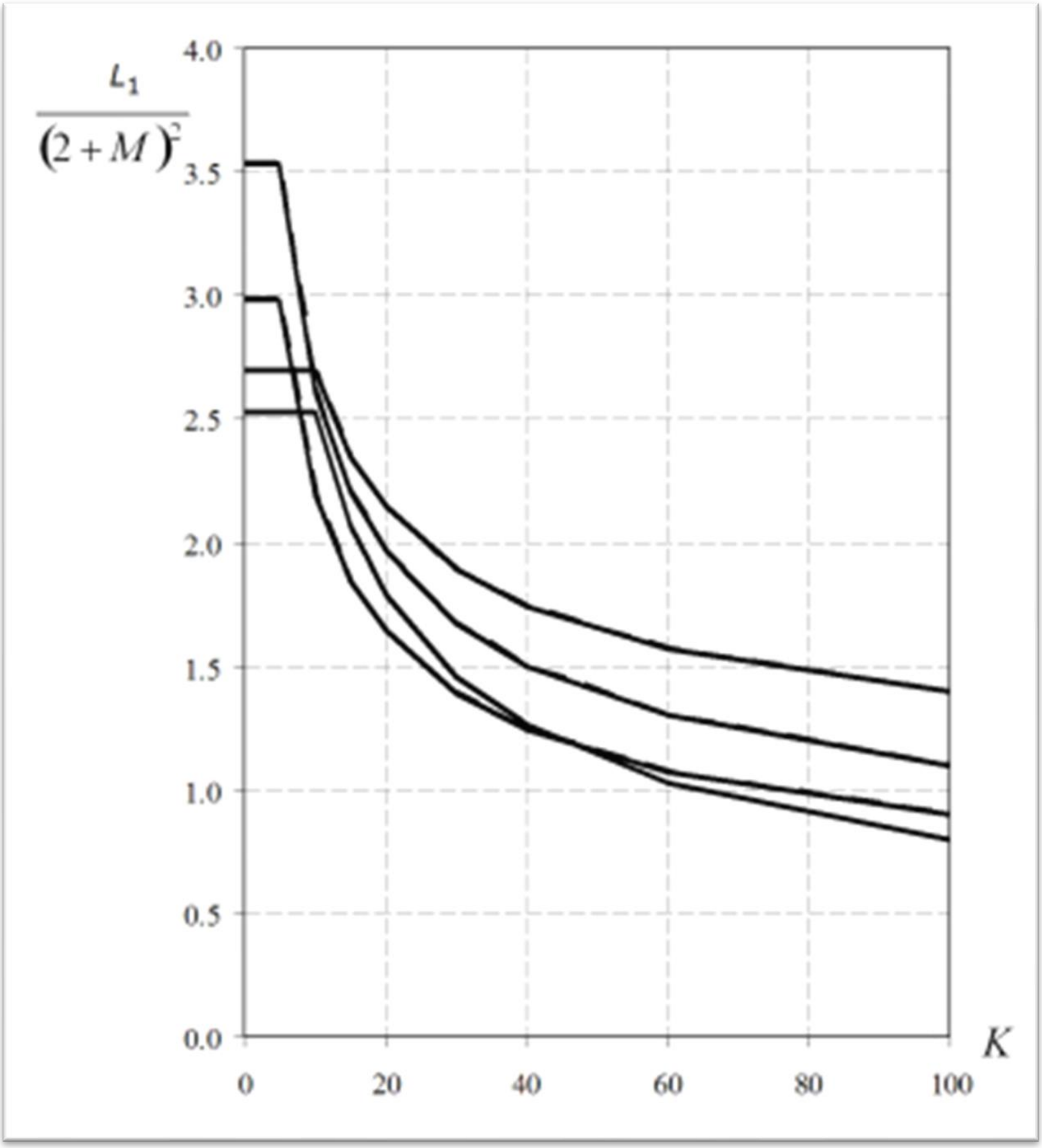

Figure 2-20: Minimum weight for a pipe on clay, Y = 10.τ / 1000, 0.006 ≤ N ≤ 0.024, Gc = 0.556 (DNV-RP-F109, 2017)

Table 2-8: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, $G_c = 1.11$ (DNV-RP-F109)

$G_c = 1.11$								
M	$N \le 0.003$				$0.006 \le N \le 0.024$			
	C_1	C_2	C_3	K_b	C_1	C_2	C_3	K_b
≤ 0.2	2.1	1	0.5	15	1.4	4	0.5	15
0.4	2.4	2	0.5	15	1.1	7	0.5	15
0.5	2.4	2	0.5	15	1.5	5	0.5	15
0.6	1.9	6	0.5	15	1.6	5	0.5	15
0.8	2.2	8	0.5	15	1.9	6	0.5	15
1.0	2.2	8	0.5	15	2.2	6	0.5	15
≥ 1.5	2.4	8	0.5	15	2.0	8	0.5	15

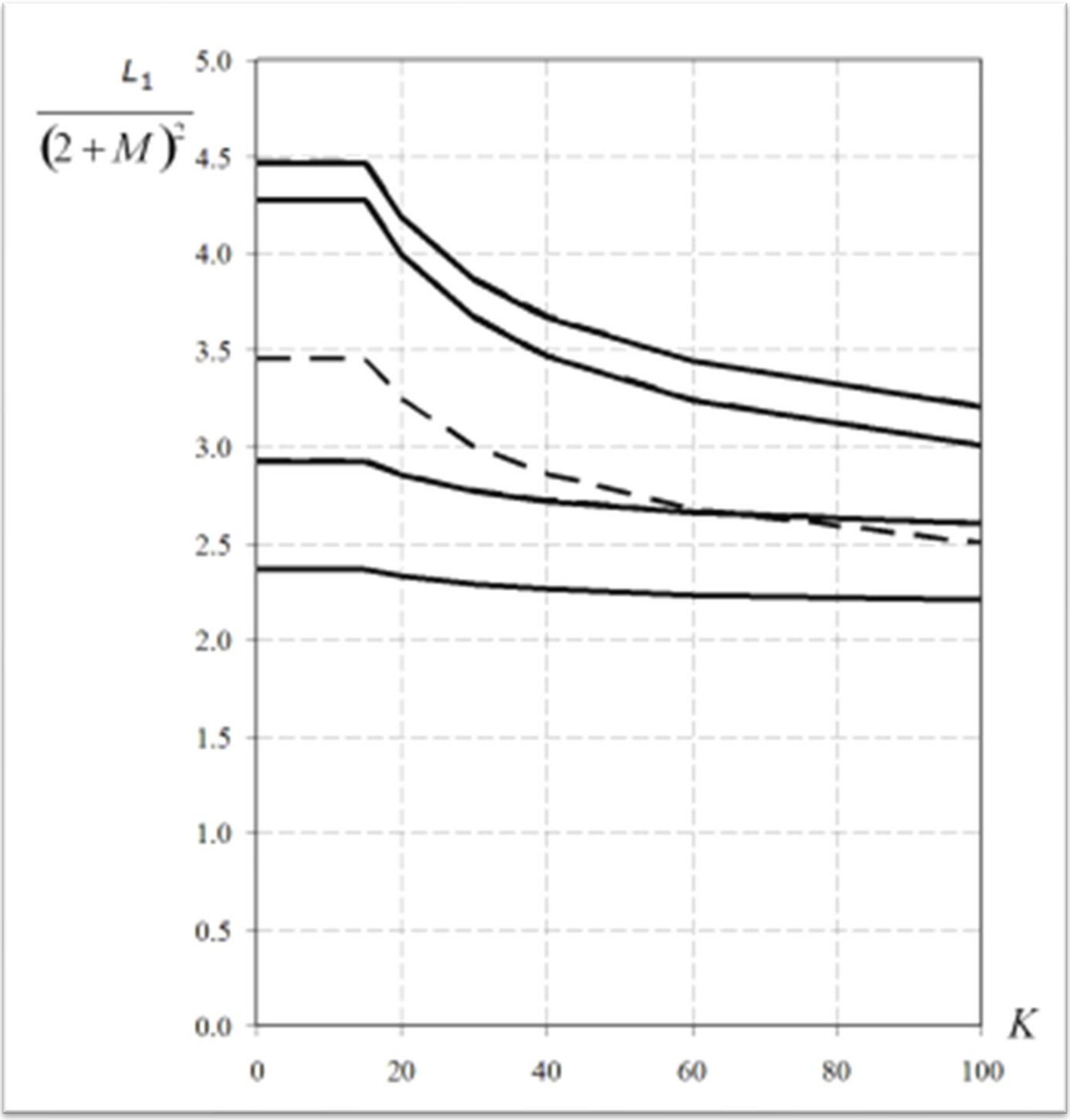

Figure 2-21: Minimum weight for a pipe on clay, Y = 10.τ / 1000, N ≤ 0.003, Gc = 1.11 (DNV-RP-F109, 2017)

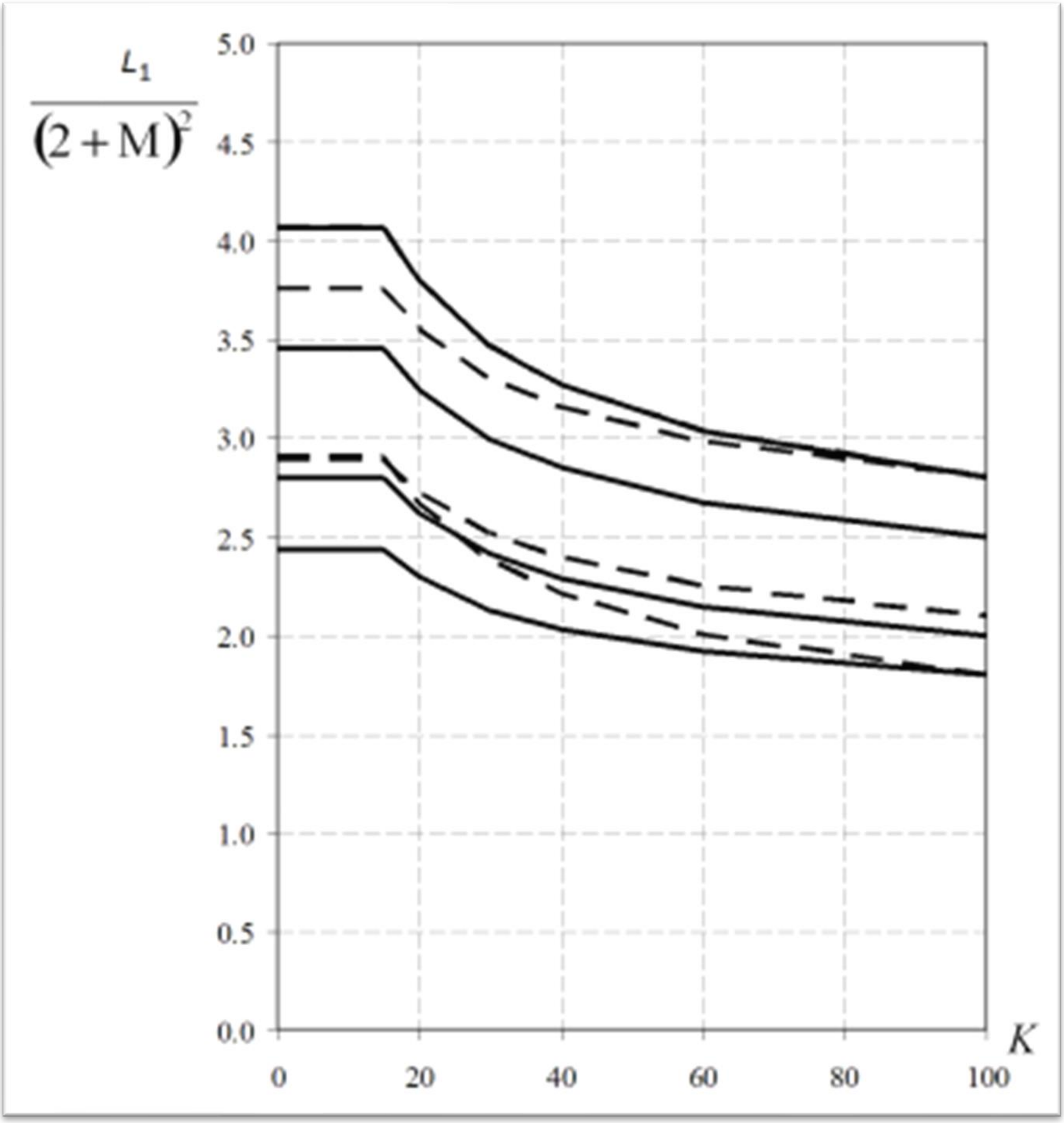

Figure 2-22: Minimum weight for a pipe on clay, Y = 10.τ / 1000, 0.006 ≤ N ≤ 0.024, Gc = 1.11 (DNV-RP-F109, 2017)

Table 2-9: Parameters for calculating minimum weight, $L_{10}/(2 + M)^2$, for pipe on clay, $G_c = 2.78$ (DNV-RP-F109)

$G_c = 2.78$								
M	$N \leq 0.003$				$0.006 \leq N \leq 0.024$			
	C_1	C_2	C_3	K_b	C_1	C_2	C_3	K_b
≤ 0.2	3.4	1	0.5	20	2.7	3	0.5	20
0.4	3.4	1	0.5	20	2.4	4	0.5	20
0.5	3.0	4	0.5	20	2.2	7	0.5	20
0.6	3.2	6	0.5	15	1.9	9	0.5	15
0.8	2.4	12	0.5	15	1.9	12	0.5	15
1.0	2.3	12	0.5	15	1.5	14	0.5	15
1.5	2.3	12	0.5	15	1.5	14	0.5	15
2.0	2.3	12	0.5	15	1.5	14	0.5	15
4.0	2.3	12	0.5	15	1.5	14	0.5	15
≥ 4.0	2.3	12	0.5	15	1.5	14	0.5	15

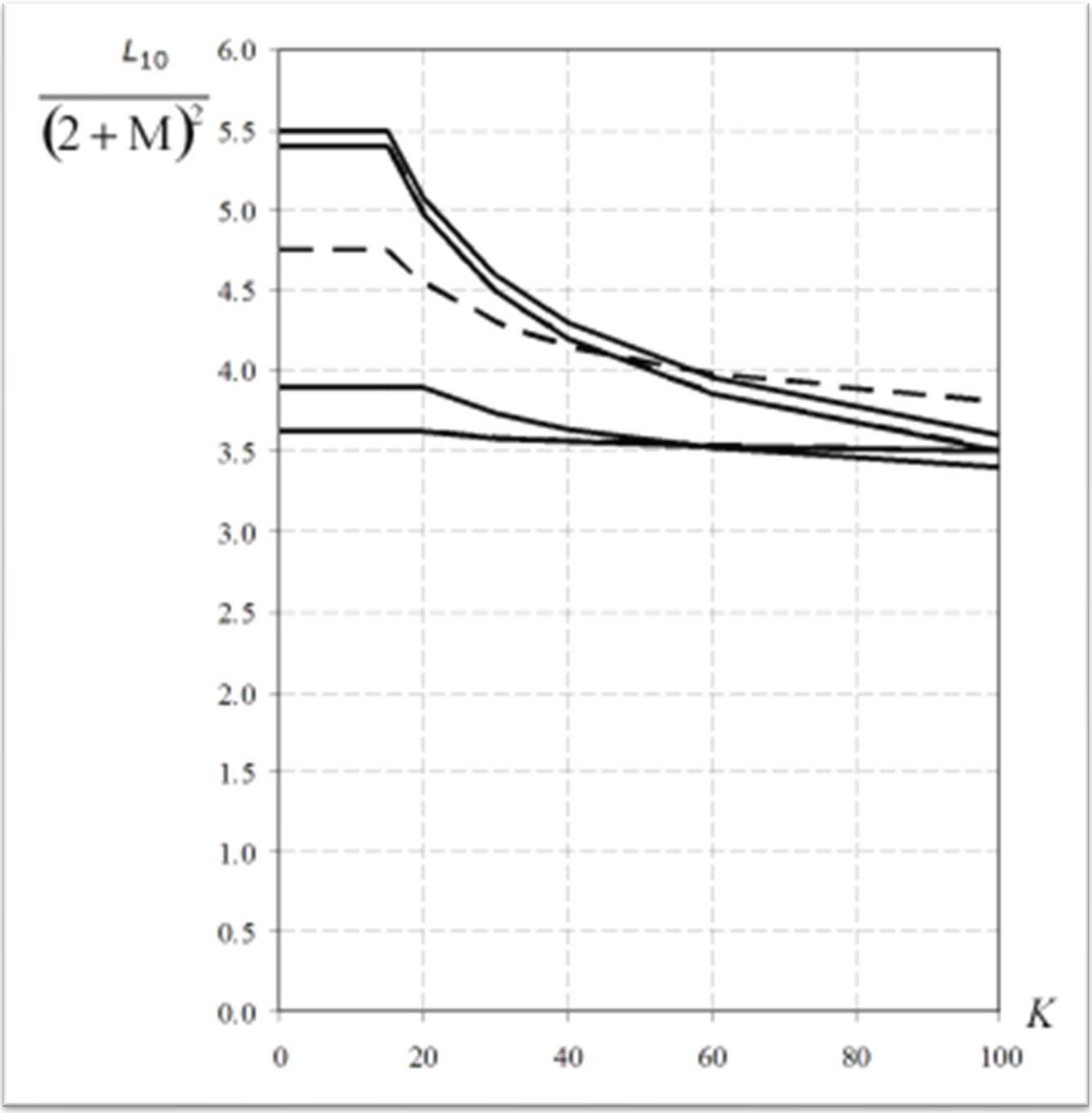

Figure 2-23: Minimum weight for a pipe on clay, Y = 10.τ / 1000, N ≤ 0.003, Gc = 2.78 (DNV-RP-F109, 2017)

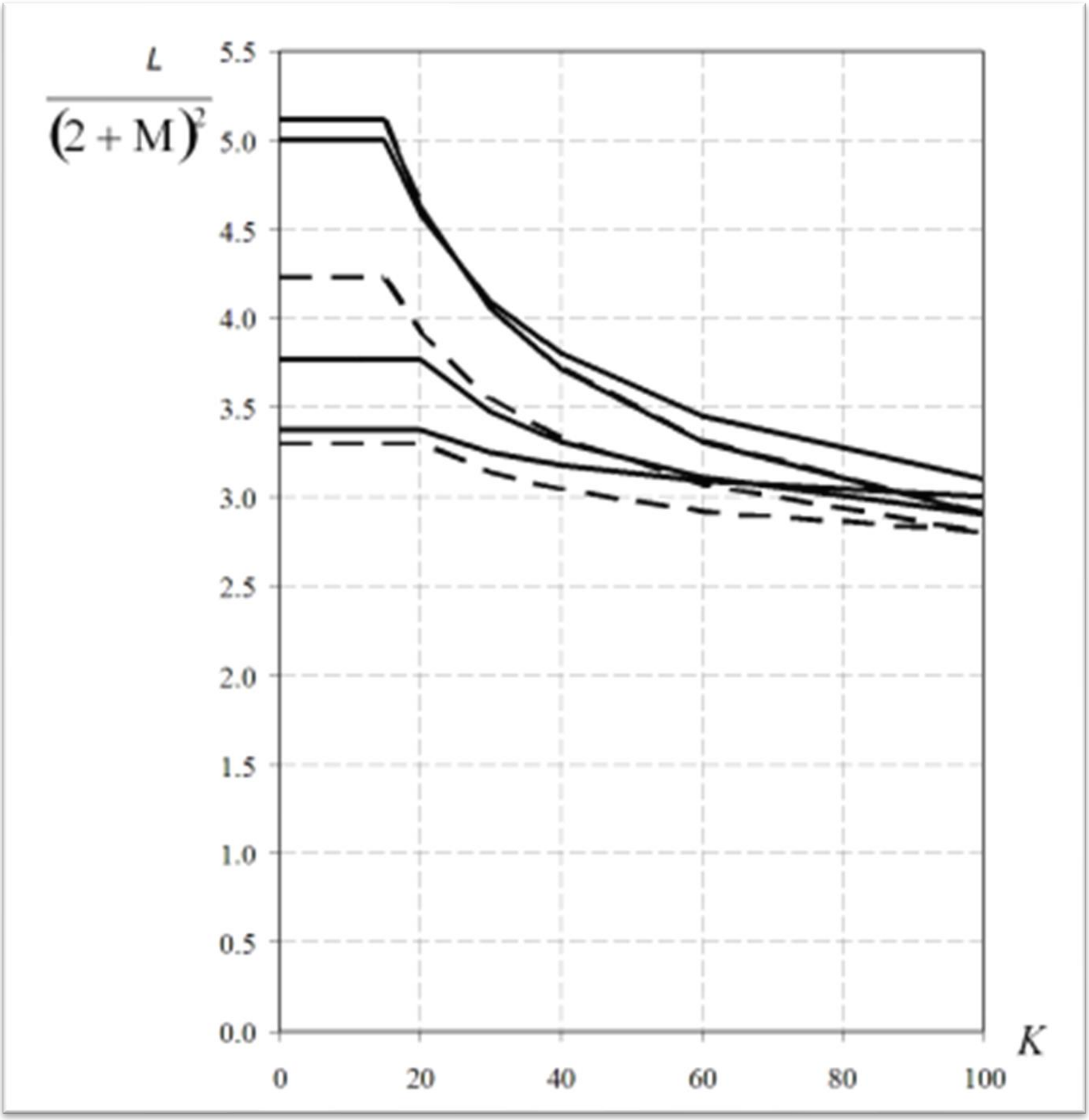

Figure 2-24: Minimum weight for a pipe on clay, Y = 10.τ / 1000, 0.006 ≤ N ≤ 0.024, Gc = 2.78 (DNV-RP-F109, 2017)

2.5.4.3 *Dynamic Lateral Stability Analysis*

This analysis intends to “predict the lateral displacement of pipes experiencing hydrodynamic forces from waves and currents during the design sea state. The soil's resisting force constituents are friction and a passive resistance term dependent on the soil penetration depth”. Furthermore, the modelling of finite beam elements in the pipe accounts for end conditions. Thus, a mass point can be used to model a pipe with negligible end effects. (Marineman, 2015)

The Dynamic Lateral Stability Analysis method predicts pipe displacement during a design storm event. Dynamic finite element analyses are the best method to use. However, the use of the method has been minimal due to the lack of need for replacing the Simplified and Generalized methods with an advanced Finite Element method in areas where Concrete Weight Coating (CWC) can be used for stability. In addition, the availability of design tools necessary for this method is also not adequate (Marineman, 2015). The two most used Finite Element (FE) based special response pipe stability packages are PONDUS and AGA software. (Bai, 2005).

Amlashi (2017) states that construction delays and cost escalations caused by the uncertainties of soil conditions are mainly due to the need for accounting for the complex interaction between waves/currents, the pipe, and seabed. Additionally, the Dynamic Lateral Stability Analysis typically validates other simplified methods (e.g., Generalized Analysis Method). Therefore, it is often used to analyze a pipe's critical areas when a detailed assessment is required for uncertainties in design parameters.

3. Methodology

This study includes a case study in which two HDPE pipes were installed at Richards Bay, South Africa. In this project, the Scandinavian method was used together with two programs to calculate pipe displacement.

First, the results of the case study will be presented. After that, a comparison will be made with the allowable displacements that would have been determined for that project if the Force Balance Method, Simplified Stability, Generalized Stability, and Dynamic Analyses; Absolute Lateral Static Stability Method, Generalized Lateral Stability Method, and Dynamic Lateral Stability Analysis had been used for that project. In addition to that, the required pipe weighting for each individual method will be calculated and compared to each other and all those results will be used as inputs for the Multi-Criteria Analysis.

The Multi-Criteria Analysis will include two Sensitivity Analyses to confirm the validity of the MCA results. The main recommendations will be based on the method which scores the highest in the MCA, but there will also be a consideration on the theory that is provided in the Literature Study.

4. Case Study

Richards Bay, South Africa

“Two High-Density Polyethylene (HDPE) pipelines of 0.9m OD (4290m long) and 1m OD (5450m long) were used for disposing of effluent. The effluent consists primarily of waste gypsum from a fertilizer plant, while the bulk of the buoyant effluent consists of waste from a large paper pulp mill. The pipelines were initially designed using the Scandinavian Design Procedure (SDP) for non-metal pipelines”. (Pos, Russel and Zwamborn, 1986)

“The displacements of the 0.9m OD pipeline sections were calculated with a computer program. The results indicated that movements of 1 – 2 m could occur. The requirement for these results to be considered acceptable was the absence of obstructions by rock outcrops. The friction tests show that friction coefficients could be less than 1”. (Pos, Russel and Zwamborn, 1986)

Pipeline Movement Calculations:

According to the CSIR Report (1985), Two pipeline movement programs, called "LARSEN" and LARSV," were developed by Prof. Ian Larson of the Royal Institute of Technology, Stockholm, Sweden (Larsen, 1984). Mr. J. Moes of NRIO installed the LARSEN program on the CDC computer of the CSIR during a two-week visit to South Africa by Prof. Larsen in April 1984. “The LARSV program is an updated version of the LARSEN program, which incorporates the true Vocoidal wave kinematics, where LARSEN contains approximate seabed velocity and acceleration time variations. In addition, the programs calculate the expected (design wave) pipeline movements for the most critical sections. The numerical algorithm embodied in the computer program is based on Abbot, Larsen, and Verwey (1977)”.

The vocoidal theory is a water wave theory developed from first principles to predict wave-induced phenomena in all depths. It is expressed in terms of algebraic expressions. The following assumptions are made consider only non-breaking waves, 2D water movement, a constant water depth, a horizontal bed, frictionless flow, invariant fluid density, negligible surface tension effects, periodic wave motion, and wave propagation at constant velocity in water of constant depth. (Swart, D. and Loubser, C., 1978).

Use the following force coefficients:

$C_M = 2$

$C_D = 0.7$

$C_L = 0$ (Lift coefficient)

4.1 Case Study Results

4.1.1 Site Data

According to the CSIR Report (1985) the site conditions are as follows:

- The seabed consists of sand
- Mdisp for the 0.9m OD pipe = 652.1 kg/m
- Mdisp for the 1m OD pipe = 805 kg/m
- U = 0.41m/s

According to Table 13 in the CSIR (1985) Report:

The average maximum values of the 0.9m for the following parameters are as follows:

- $F_{L\ max} = 0$ (Assumed $C_L = 0$)
- $F_{D\ max} =$ 1.49 kN/m
- $F_{M\ max} =$ 2.36 kN/m

4.1.2 Case Study Assumptions:

- The pipe is D/4m clear of the bed
- $C_M = 2$
- $C_D = 0.7$
- $C_L = 0$
- Listed anchor weights are all submerged weights

4.1.3 Weight Calculations

These weight calculations were done in Appendix C of the CSIR Report (1985)

Weight of 0.9m OD pipe

Outside diameter = 0.9m

Inside diameter = 0.9 – (2*0.04)

= 0.82m

U = 0.41m/s

Mass density = 955 kg/m^3

Cross-sectional area = 0.1081m^2

Weight in air = 1.01 kN/m

Weight below seawater = 1.01 – 1.09

= - 80 N/m

Weight of star weight for 0.9m OD pipe:

Weight in air = 2185kg * 9.81

= 21.43 kN

Weight below seawater = (2185 – 2185/2400 * 1025) * 9.81

= 12.28 kN

Weight of fresh water in pipe

Weight of fresh water in air = $\pi * 0.41^2 * 1000 * 9.81$

= 5.18 kN/m

Weight of fresh water below seawater = $(528.1 - \pi * 0.41^2 * 1025) * 9.81$

W_s = - 129 N/m

Weight of pipe and star weights below seawater

Weight of 3m length of pipe filled with fresh water and with two star weights all below seawater = 2 * 12.28 – 3 * (0.08 + 0.129)

= 23.93 kN

Weight per meter = 23.93 / 3

= 7.977 kN/m

The results of expected lateral movements for a friction coefficient of 1:

- For the 1:1 – 0.07m to 0.19m
- For the 1:10 – 0.26m to 0.55m

- For the 1:50 – 0.65m to 1.09m
- For the 1:100 – 0.87m to 1.34m.

Table 4-1 below summarizes the results of pipe displacement results (CSIR, 1985). In this case study, the calculation of pipe displacement through the Scandinavian method required two programs. A numerical algorithm was embodied in the computer program, and it was used by the program to produce the displacement results. Therefore, the assumption is that there is a need for the programs to be incorporated into the prediction of pipeline displacement (CSIR, 1985).

Table 4-1: Lateral Displacements along sections of the 0.9m OD pipeline

Chainage (m)	Return period (years)	MSL depth (m)	Maximum wave height (m)	Mean angle of incidence (degrees)	Pipe OD (m)	Friction coefficient	Installed weighting expressed as a % of displaced weight	Absolute Displacement	
								Maximum excursion (m)	Maximum residual displacement (m)
1 000	1:1	8.5	6.6	48	0.9	1	50	0.12	0.05
1250 1250	1:1 1:10	12 12	8.9 9.5	50 50	0.9 0.9	1 1	50.1 50.1	0.19 0.3	0.11 0.18
2000	1:100	16.7	12.5	52	0.9	1	40.1	1.02	0.51
3500 3500 3500 3500	1:1 1:10 1:50 1:100	20 20 20 20	8.6 10.6 11.9 12.5	49 49 49 49	0.9 0.9 0.9 0.9	1 1 1 1	30.8 30.8 30.8 30.8	0.07 0.26 0.65 0.87	0.01 0.05 0.18 0.26
4000 4000 4000 4000 4000	1:1 1:10 1:50 1:50 1:100	21 21 21 21 21	9.3 11.5 12.9 12.9 13.5	52 52 52 52 52	0.9 0.9 0.9 0.9 0.9	1 1 1 0.75 1	30.8 30.8 30.8 30.8 30.8	0.09 0.55 1.09 1.85 1.34	0.02 0.09 0.18 0.2 0.17
4290 4290 4290 4290 4290 4290	1:1 1:10 1:50 1:50 1:50 1:100	24 24 24 24 24 24	10 12.3 13.8 13.8 13.8 14.5	53 53 53 53 53 53	0.61 0.61 0.61 0.61 0.61 0.61	1 1 1 0.75 0.5 1	33.2 33.2 33.2 33.2 33.2 33.2	0.07 0.39 0.76 1.3 2.01 0.98	0.06 0.35 0.74 1.25 1.84 0.96

4.2 Results from applying other methods to case study

4.2.1 Displacement Results

The main challenge of comparing displacements of the different methods discussed in this study is that none explicitly have equations or calculations for calculating an exact displacement value. Some allow no displacement; some provide ranges of allowable displacement values, and others specify the maximum allowable displacement.

Table 4-2 below shows a comparison of the displacement allowances that would have been used for each method by using the two pipe diameters, 0.91m and 0.61m, that were used in the case study.

Table 4-2: Displacement Allowances of Different Methods for the Case Study

Methods		Force Balance Method	DNV-RP-F109			
			Simplified Stability Analysis	Generalized Stability Method	Absolute Lateral Static Stability Method	Generalized Lateral Stability Method
Displacement allowance		0	0 – 20m	0 – 40D	0	0.5D – 10D
Case Study Results	D = 0.9m	0	0 – 20m	0 – 36m	0	0.45m – 9m
	D = 0.61m	0	0 – 20m	0 – 24.4m	0	0.305m - 6.1m

4.2.2 Weighting Results

Another approach for comparing the methods is using each method to determine the required pipe weight, then compare the results and discuss the findings. When it comes to the Dynamic Analysis of DNV-RP-E305 and the Dynamic Lateral Stability Analysis of DNV-RP-F109, determining the required weight would need finite element analyses and dynamic modelling to be done, which are not part of the scope of this study. Hence, the 2 methods have been excluded in this section.

Due to the limitation of site parameters provided in the CSIR Report (1985) there are many assumptions that needed to be made for the calculations. Note – for simplification purposes, all calculations were focused on the 0.9m OD pipe instead of both pipes.

General Assumptions applicable to all the method calculations:

- M = 0.6
- K = 5
- N = 0.048
- μ = 0.2

4.2.2.1 *Generalized Stability Analysis – DNV-RP-E305*

The generalized response of the pipeline in a given sea state is controlled by non-dimensional parameters. One of those parameters is the pipe weight parameter.

Using fig Figure 2-1 and assuming δ = 10, T = 500

$\sqrt{(L)} \quad = 3,$

Thus, L = 9

$W_s = L / (0.5 * \rho_w * D * U_s^2)$

$= 9 / (0.5 * 1025 * 0.9 * 0.41^2)$

$= 0.116$ kN/m

4.2.2.2 *Simplified Stability Analysis – DNV-RP-E305*

$F_w = 0.7$ (for sand) – DNV-RP-E305

$W_S = [\ ((F_D + F_L) + \mu * F_L) / \mu)]_{max} * F_w$

$= ((1.49 + 2.36) / 0.2) * 0.7$

$= 13.48$ kN/m

4.2.2.3 *Force Balance Method*

<u>Assumptions:</u>

$\gamma_{st} = 1.1$ (section 2.5.1)

$\gamma_{st} (F_D – F_M) = \mu(W_{sub} – F_L)$

$W_{sub} \quad = [\gamma_{st} (F_D – F_M)] / \mu$

$= (1.1*(1.49 – 2.36)) / 0.2$

$= 4.785$ kN/m

4.2.2.4 Absolute Lateral Static Stability Method – DNV-RP-F109

<u>Assumptions:</u>

- Only friction is accounted for on the resistance side.

Table 4-3: Peak horizontal load coefficients

C^*_y		K*										
		2.5	5	10	20	30	40	50	60	70	100	≥140
M*	0.0	13.0	6.80	4.55	3.33	2.72	2.40	2.15	1.95	1.80	1.52	1.30
	0.1	10.7	5.76	3.72	2.72	2.20	1.90	1.71	1.58	1.49	1.33	1.22
	0.2	9.02	5.00	3.15	2.30	1.85	1.58	1.42	1.33	1.27	1.18	1.14
	0.3	7.64	4.32	2.79	2.01	1.63	1.44	1.33	1.26	1.21	1.14	1.09
	0.4	6.63	3.80	2.51	1.78	1.46	1.32	1.25	1.19	1.16	1.10	1.05
	0.6	5.07	3.30	2.27	1.71	1.43	1.34	1.29	1.24	1.18	1.08	1.00
	0.8	4.01	2.70	2.01	1.57	1.44	1.37	1.31	1.24	1.17	1.05	1.00
	1.0	3.25	2.30	1.75	1.49	1.40	1.34	1.27	1.20	1.13	1.01	1.00
	2.0	1.52	1.50	1.45	1.39	1.34	1.20	1.08	1.03	1.00	1.00	1.00
	5.0	1.11	1.10	1.07	1.06	1.04	1.01	1.00	1.00	1.00	1.00	1.00
	10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 4-4: Peak vertical load coefficients

C^*_z		K*										
		≤2.5	5	10	20	30	40	50	60	70	100	≥140
M*	0.0	5.00	5.00	4.85	3.21	2.55	2.26	2.01	1.81	1.63	1.26	1.05
	0.1	3.87	4.08	4.23	2.87	2.15	1.77	1.55	1.41	1.31	1.11	0.97
	0.2	3.16	3.45	3.74	2.60	1.86	1.45	1.26	1.16	1.09	1.00	0.90
	0.3	3.01	3.25	3.53	2.14	1.52	1.26	1.10	1.01	0.99	0.95	0.90
	0.4	2.87	3.08	3.35	1.82	1.29	1.11	0.98	0.90	0.90	0.90	0.90
	0.6	2.21	2.36	2.59	1.59	1.20	1.03	0.92	0.90	0.90	0.90	0.90
	0.8	1.53	1.61	1.80	1.18	1.05	0.97	0.92	0.90	0.90	0.90	0.90
	1.0	1.05	1.13	1.28	1.12	0.99	0.91	0.90	0.90	0.90	0.90	0.90
	2.0	0.96	1.03	1.05	1.00	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	5.0	0.91	0.92	0.93	0.91	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	10	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90

The required weight is:

$$L^* = C^*_y/\mu + C^*_z$$
$$= 3.3/0.2 + 2.36$$
$$= 18.86$$

$$W_s = L / (0.5 * \rho_w * D * U_s^2)$$
$$= 18.86 / (0.5 * 1025 * 0.9 * 0.41^2)$$
$$= 0.243 \text{ kN/m}$$

4.2.2.5 *Generalized Lateral Stability Method – DNV-RP-F109*

Using Table 2-2:

$$L_{stable} / (2 + M)^2 = 1.13$$
$$L_{stable} = 1.13 * (2 + 0.6)^2$$
$$= 7.64$$

Using Table 2-3 :

$$L_{10} / (2 + M)^2 = 0.79$$
$$L_{10} = 0.79 * (2 + 0.6)^2$$
$$= 5.34$$

$$W_{s\ stable} = L / (0.5 * \rho_w * D * U_s^2)$$
$$= 7.64 / (0.5 * 1025 * 0.9 * 0.41^2)$$
$$= 0.0985 \text{ kN/m}$$

$$W_{s\ 10} = L / (0.5 * \rho_w * D * U_s^2)$$
$$= 5.34 / (0.5 * 1025 * 0.9 * 0.41^2)$$
$$= 0.0689 \text{ kN/m}$$

4.2.2.6 *Discussion on weighting results*

Table 4-5 below summarizes results produced by the weighting calculations done for each method:

Table 4-5: Summary of the results of Required Weight Calculations

	Scandinavian	Generalized Stability Analysis	Simplified Stability Analysis	Force Balance Method	Absolute Lateral Static Stability	Generalized Stability Analysis
Required Weight (kN/m)	7.977	0.116	13.48	4.785	0.243	0.0689 – 0.0985

The results have shown that the method which requires the least amount of weight is the DNV-RP-F109's Generalized Stability Analysis. The DNV-RP-E305's Generalized Stability Analysis has the second least required weight. The method requiring the largest weight is the Simplified Stability Analysis, followed by the Scandinavian Method, Force Balance Method and Absolute Lateral Static Stability respectively. There is a significant gap between these four highest methods and the two Generalized methods.

These results prove that preventing a pipeline from moving requires making it heavier than a pipeline that is allowed to move. This also supports the statement that it will always be more expensive to use the Force Balance Method, Simplified Stability Analysis and Absolute Lateral Static Stability Method. It is interesting that the Scandinavian Method also falls into this group of methods which require more weight. Perhaps contributing factors to this result are that the pipe is only allowed to move once or twice a year, so it is somewhat more limited than the Generalized Methods and contrary to the other methods, the weight is added through anchor blocks instead of concrete weight coating. Perhaps the gaps between the anchor block weights have a negative impact on the distribution of the weight along the pipe.

From these results, it is evident that the most cost-effective method is the Generalized Stability Analysis. However, it is important to note that in this exercise, it is unknown what results could have been produced by the two Dynamic Analyses but due to finite element analyses and dynamic modelling not being in the scope of this study, their results could not be determined.

5. Multi-Criteria Analysis

5.1 Overview

Adopting an MCA approach can bring structure, analysis, and transparency to the decision-making process. In the evaluation of the suitability of any option, many factors or criteria need to be considered. A Multi-Criteria Analysis aims to rate each option against weighted criteria to determine the preferred option across the entire spread of criteria. The criteria weightings should prioritize specific project elements based on their importance to the project. (Ligteringen and Velsink, 2012)

5.2 Scoring Method

The adopted scoring methodology was as follows: (Ligteringen and Velsink, 2012)

- Rationalize options with fatal flaws or logical limitations.
- Each set of criteria were scored qualitatively by giving a relative score. The goal was to rate each option against each criterion and award a score out of five (5) based on the options' performance in those criteria (refer to Table 5-1 below).
- Compared to the other options, these scores were then tallied to a percentage score for the entire option.
- The goal is to select a well-balanced solution that consistently scores well across many criteria

Table 5-1: Basis for Scoring Criteria

Score	Rating
5	Highly Favourable
4	Favourable
3	Neutral
2	Unfavourable
1	Highly Unfavourable

5.3 MCA Results

Table 5-2 below shows the scoring outcome during the Multi-Criteria Analysis of the eight displacement methods.

Table 5-2: Results of the Multi-Criteria Analysis on the Displacement Methods

	Scores					
Criteria	Force Balance Method	Simplified Stability Analysis	Generalized Stability Method	Absolute Lateral Stability Method	Generalized Lateral Stability Method	Scandinavian Method
Displacement Allowance	1	2	5	1	4	3
Method Age	1	2	2	3	5	4
Required Weighting	3	1	5	4	5	2
Affordability	3	1	5	4	5	2
Totals	**8**	**6**	**17**	**12**	**19**	**11**

5.4 Discussion on MCA results

The scoring of displacement allowance is based on the results presented in Table 4-2. The Force Balance Method and Absolute Lateral Stability Method received the lowest scores because they both allow zero displacement, which ultimately makes them more expensive because they require heavier weighting to achieve this. The simplified Stability Analysis also scored low on this criterion because, although it does allow up to 20m maximum displacement, this makes it more rigid than the rest of the methods which incorporate the pipe diameter in their calculations. Incorporating pipe diameter in the calculation is critical because it caters better to teach specific case study. The rest of the methods received higher scoring but were ranked according to the order of the results they produced in Table 4-2. The Generalized Stability Method got the highest score because it produced the highest maximum allowable displacement. An important limitation of the Scandinavian Method is that it only allows pipe movement once or twice a year.

The scoring of Date Released criteria is based on the timeframe of each method's release. In terms of assessing each method's validity and relevance to the present time, it is also very important to account for the date in which each method was released. The older a method is, the more likely it is to be outdated. The Force Balance Method received the lowest score because it is the oldest method followed by the methods in the DNV-RP-E305 code (Simplified Stability Analysis and Generalized Stability Method), which were superseded by the methods in the DNV-RP-F109 code. However, the fundamental principles of the Absolute Lateral Stability Method are more synonymous to the older Force Balance and Simplified Stability Analysis. Hence it received a lower scoring to the Generalized Stability Method. While the case study which used the Scandinavian method is a very old project (at the time there was not enough information available on the method), the method itself has become more updated with time.

The scoring of required weighting is based on the results summarized in Table 4-5 of the required weighting calculations that were done for each method. These scores are identical to the scoring done for Affordability because cost is directly proportional to required weighting. The heavier a pipe needs to be, the more money it will cost to achieve the weight requirement. The Generalized stability methods received the highest scores because they both required the least amount of weight and hence would be the cheapest. The rest were scored in the order of their ranking in terms of their results. Hence, the Simplified Stability Analysis received the lowest score because it required the highest weighting, which made the most expensive and least affordable method.

With the highest overall scoring from the ratings, the Multi-Criteria Analysis indicates that the Generalized Lateral Stability Method is the most recommendable method for determining displacement. The main factors that make this method most favourable is that it is not outdated, and it requires the least amount of weighting, which makes it the most affordable.

5.5 MCA Sensitivity Analysis

To test the sensitivity of the MCA for variations in ratings, two additional MCAs are conducted, with weightings shifted to show how varying project priorities will affect the MCA. This exercise allows an evaluation of the robustness of certain alternatives – when an alternative consistently scored well across multiple MCAs, it enforces its likelihood of moving forward as a preferred option. (Ligteringen and Velsink, 2012)

The two additional MCA cases include the following:

5.5.1 MCA Alt 1 – Displacement Allowance

This MCA case was weighted to prioritize Displacement Allowance by allocating 40% weighting to Displacement Allowance and allocating 20% to all the rest. The results of this weighting are shown in Table 5-3 below:

Table 5-3: MCA Sensitivity Analysis weighted to prioritize Displacement Allowance

Criteria	Weighting	Force Balance Method	Simplified Stability Analysis	Generalized Stability Method	Absolute Lateral Stability Method	Generalized Lateral Stability Method	Scandinavian Method
Displacement Allowance	40%	0.4	0.8	2.	0.4	1.6	1.2
Method Age	20%	0.2	0.4	0.4	0.6	1	0.8
Required Weighting	20%	0.6	0.2	1	0.8	1	0.4
Affordability	20%	0.6	0.2	1	0.8	1	0.4
	Totals	**1.8**	**1.6**	**4.4**	**2.6**	**4.6**	**2.8**

The results of this sensitivity analysis indicate that the Generalized Lateral Stability Method continues to produce the highest score when Displacement Allowance is prioritized, and the weighting is allocated in the chosen manner. While the ranking order of scoring total results has slightly changed, the Simplified Stability Analysis continues to produce the lowest total score.

5.5.2 *MCA Alt 2 – Required Weighting*

This MCA case was weighted to prioritize Required Weighting by allocating 40% weighting to Required Weighting and allocating 20% to all the rest. The results of this weighting are shown in Table 5-4 below:

Table 5-4: MCA Sensitivity Analysis weighted to prioritize Flexibility

Criteria	Weighting	Force Balance Method	Simplified Stability Analysis	Generalized Stability Method	Absolute Lateral Stability Method	Generalized Lateral Stability Method	Scandinavian Method
Displacement Allowance	15%	0.2	0.4	1	0.2	0.8	0.6
Method Age	15%	0.2	0.4	0.4	0.6	1	0.8
Required Weighting	40%	1.2	0.4	2	1.6	2	0.8
Affordability	15%	0.6	0.2	1	0.8	1	0.4
	Totals	**2.2**	**1.4**	**4.4**	**3.2**	**4.8**	**2.6**

Once again, the sensitivity analysis results have shown that the Generalized Lateral Stability Method has the highest total score, even when the Required Weighting is prioritized. This time the order of total score ranking is the same as the results of the initial Multi-Criteria Analysis shown in Table 5-2.

6. Discussion

The prediction of pipeline displacement plays a critical role in the process of designing a pipeline. If on-bottom stability cannot be achieved by a designed pipe in the environment where it will be installed, the pipeline will fail long before it's design life.

The pipe design process generally involves starting with a trial pipe weight by using a simplified analysis, then calculating the pipe diameter and determining the non-dimensional parameters to attain the required weight parameter. If the relative change in diameter is unacceptable, the diameter must be revised and used to calculate new parameters.

Most methods for predicting pipe displacement are dependant on pipe diameter. That is why displacement plays a major role in the pipe design process. If the pipe diameter is sufficient, it will produce a displacement result that does not exceed the maximum allowable displacement or falls within the required range of that specific method.

Therefore, once it is found that the designed pipe's diameter is producing an estimated displacement that exceeds the maximum allowable displacement or falls out of the required range of displacement, it is deemed unacceptable, and the Designer must revert to the design process with a revised pipe diameter or by adding weight to the pipe.

The Case Study Results show that no matter the pipe diameter, the Force Balance Method and the DNV-RP-F109's Absolute Lateral Stability method will always not allow any pipe displacement. Furthermore, the DNV-RP-E305's Simplified Stability Analysis is also not dependant on pipe diameter. Its maximum allowable displacement is 20m. Finally, the DNV-RP-E305's Generalized Stability Method allows a maximum pipe displacement of 40D, which is 36m for the 0.9m diameter pipe, and 24.4m for the 0.61m diameter pipe. However, It is important to note that such large displacements are risky, much so if the seafloor and founding conditions are uncertain or variable.

The DNV-RP-F109's Generalized Lateral Stability Method is the only method that gives a specific range. The allowable pipe displacement must be between 0.5D and 10D. This gives a range of 0.45m – 9m for the 0.9m diameter pipe and 0.305m – 6.1m for the 0.61m diameter pipe.

According to the Case Study Results, the DNV-RP-E305's Generalized Stability Method allows the highest maximum displacement out of all the methods. Ideally, the method which allows the highest maximum displacement would be the best option. However, this is not the only factor that can be used for determining the best option. Another thing to consider is that each project's pipe diameter plays a considerable role. For instance, the allowable displacement of the Simplified Stability Analysis is not dependant on pipe diameter. It will always be fixed at 20m. Therefore, if the pipe diameter is small enough, the Simplified Stability Analysis can have the highest displacement for that project. But if the pipe diameter is larger, the Simplified Stability Analysis would no longer produce the highest allowable displacement.

Another contributing factor to the determination of the best method for a project is the site conditions. For instance, the Generalized Lateral Stability Method is only relevant for pipes on sand and clay. So, if a pipe is not on sand or clay, this method cannot be used for that project. Likewise, the validity of the Simplified Stability Analysis is limited to pipes that will rest on the seabed for their entire lifetime. The method is no longer relevant once the pipe is stabilized by burial. Therefore, it is essential to fully understand a site's conditions before selecting a method that will be most relevant for it.

In addition to the displacement calculations, this study has also carried out calculations for required pipe weight. Each method's calculations were done, and their results were compared to each other to determine the most recommendable method. In these results, the DNV-RP-F109's Generalized Lateral Stability Method had the lowest required pipe weight, which made it the most ideal because the less weight required, the less cost will be required.

7. Conclusions and Recommendations

The purpose of this study was to provide information on different methods that can be used to determine the displacement of marine pipelines. The methods that were discussed were the Force Balance Method; the Scandinavian Method; the DNV-RP-E306 code's Simplified Stability Analysis, Generalized Stability Analysis and

Dynamic Analysis; and the DNV-RP-F109 code's Absolute Lateral Static Stability Method, Generalized Lateral Stability Method and Dynamic Lateral Stability Analysis.

Theoretical background was provided on each method and calculations were made on the displacements and required weighting that would be produced by each method if they were all applied to the same case study.
The results of each method were used as inputs for a Multi-Criteria Analysis which was used to determine the most recommendable method (which scored the highest in the MCA). However, since the scope of this study excluded finite element analysis and dynamic modelling, the two dynamic analysis methods had to be excluded from all the calculations, results sections, and the MCA.

The results of the MCA indicated that the DNV-RP-F109's Generalized Lateral Stability Method was the most recommendable method, since it scored the highest, even after the two Sensitivity Analyses was incorporated. However, when applying the method to a specific case study, it is important to first determine whether all the requirements for using the code are fulfilled and confirm if the method is relevant for that specific case study or not.

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