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Advanced procedure for estimation of pipeline embedment on soft clay seabed

S.Y. Yu[1a], H.S. Choi[2b], K.S. Park[3c], Y.T. Kim[4c] and D.K. Kim[*1,2]

[1]*Ocean and Ship Technology, Deepwater Technology Mission Oriented Research, Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia*
[2]*Graduate School of Engineering Mastership, Pohang University of Science and Technology, 37673 Pohang, Republic of Korea*
[3]*Steel Structure Research Group, POSCO Global R&D Center, 21985 Incheon, Republic of Korea*
[4]*Environmental and Plant Engineering Research Team, Daewoo Institute of Construction Technology, 16297 Suwon, Republic of Korea*

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Abstract. In the present study, the advanced procedure has been proposed to estimate higher accuracy of embedment of pipes that are installed on soft clay seabed. Numerical simulation by OrcaFlex simulation code was performed to investigate dynamic seabed embedment, and two steps, i.e., static and dynamic analysis, were adopted. In total, four empirical curves were developed to estimate the seabed embedment including dynamic phenomena, i.e., behaviour of vessel, environmental condition, and behaviour of nonlinear soil. The obtained results were compared with existing methods (named general method) such as design code or guideline to examine the difference of seabed embedment for existing and advance methods. Once this process was carried out for each case, a diagram for estimating seabed embedment was established. The applicability of the proposed method was verified through applied examples with field survey data. This method will be very useful in predicting seabed embedment on soft clay, and the structural behaviours of installed subsea pipelines can be changed by the obtained seabed embedment in association with on-bottom stability, free span, and many others.

Keywords: seabed embedment; soft clay; dynamic installation; dynamic environment; pipe-soil interaction

1. Introduction

It is well recognized that the water depth of offshore development is getting deeper and deeper in association with high demand for natural resources, especially for hydrocarbon, due to rapid economic growth in many countries. With regards to deepwater environment, the clay seabed is widely distributed in ocean and closely related with deepwater and ultra-deepwater environment as shown in Fig. 1.

The characteristic of soft clay soil causes not only immediate settlement but also time-dependent embedment called extended settlement. Its characteristics are important variables for the structures installed on seabed and especially, for the offshore pipeline, affect the structural design and its capacity such as on-bottom stability, free-span length, and many others. This means that the seabed behaviour should be estimated and applied to the subsea structural design if there is a possibility of seabed embedment depending on its prospective characteristics such as undrained shear strength, submerged weight of soil, Poisson’s ratio, and friction coefficient. Especially, this embedment phenomenon might be defined that it is caused by dynamic behaviour due to vessel motion, environmental condition, nonlinear soil properties, and several other reasons.

This dynamic behaviours of seabed are however not carefully considered in the present design code and guidelines regarding to the subsea installation of various structures such as pipeline, flowline, umbilical, subsea systems and many others. In other words, static embedment or penetration depth by empirical formula of seabed is still assumed and applied to the design. For example, the amount of seabed embedment is obtained by simple calculation from submerged weight and reaction force using empirical formula, which is specified in current design codes (DNV 2006, 2010).

In order to overcome the gap between reality and current technology, a number of researches regarding to the pipe-soil interaction have been widely performed by several experts from the end of 20 Century in terms of the numerical simulation for the soil’s nonlinearity on the softening and large deformation of soil by using finite element method (Merifield *et al.* 2008, 2009, White *et al.* 2010), verification of numerical results by geotechnical tests (Dingle *et al.* 2008, Zhou *et al.* 2008), and development of advanced soil models considering cyclic loading (Aubeny *et al.* 2006, Randolph and Quiggin 2009). In addition, various studies on pipe and riser-soil interaction under dynamic conditions were also be conducted (Lund 2000, Elosta *et al.* 2013, Sun *et al.* 2013, Kim *et al.* 2017).

Recently, Yu *et al.* (2013) investigated on-bottom

∗Corresponding author, Senior Lecturer
E-mail: do.kim@petronas.com.my
[a]Post-doctoral research associate
[b]Professor
[c]Principal researcher
[d]Researcher

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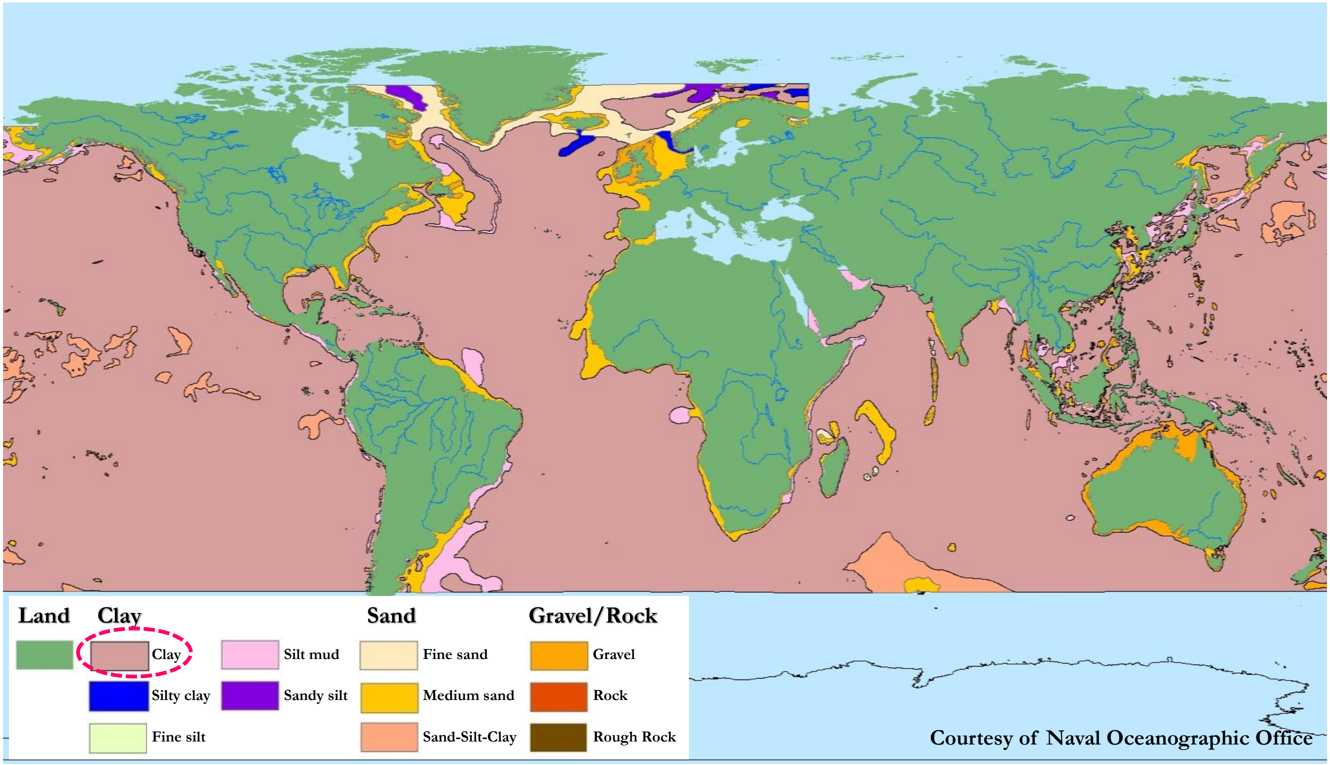


Fig. 1 Marine sediment distribution (NAVO 2013)

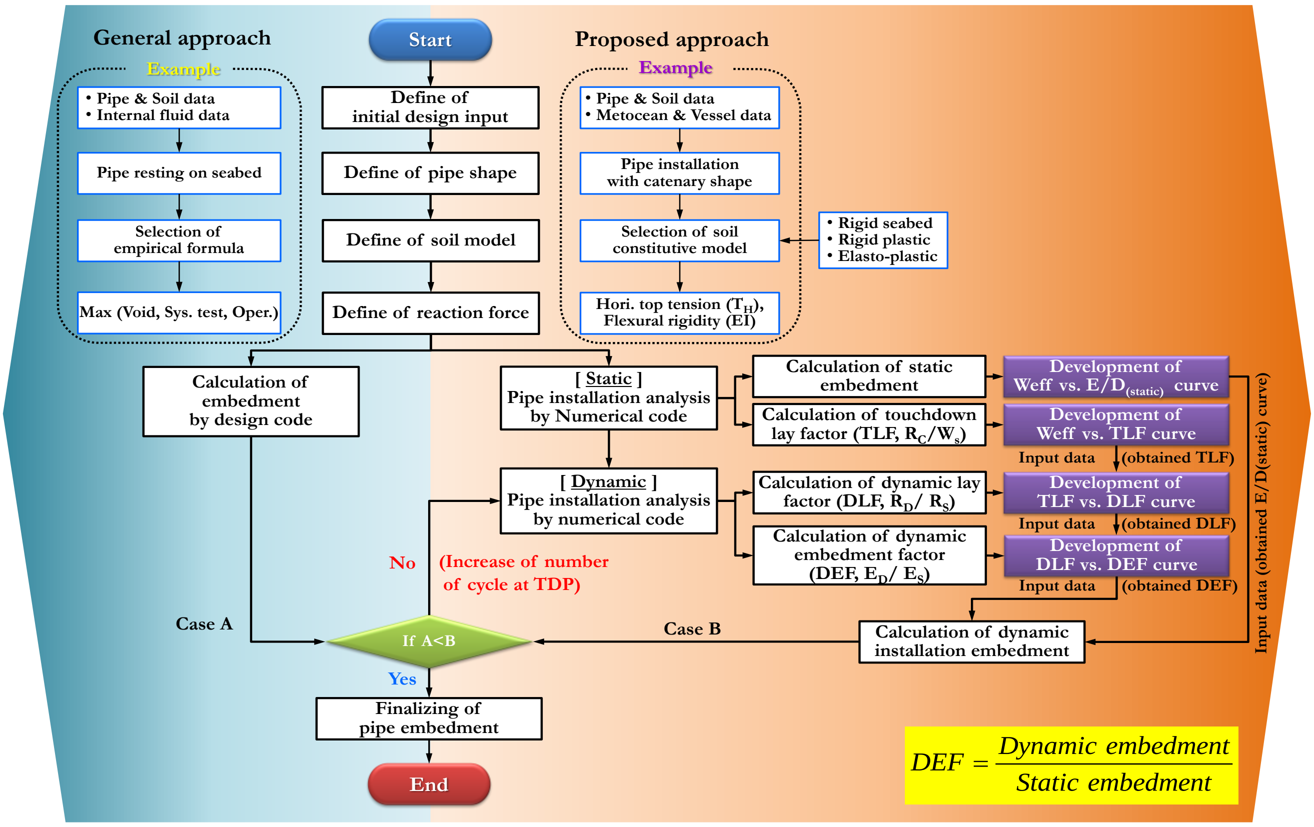


Fig. 2 Proposed procedure for estimation of pipe embedment on soft-clay seabed

stability of pipeline on the soft clay seabed and many researches are now continuously performed in world-wide. In addition, the dynamic embedment factor (DEF) concept, which can be defined as dynamic embedment divided by static embedment, has been proposed but the resolution procedure for calculation of DEF does not clearly exist now.

In this regards, advanced procedures are proposed for the estimation of pipe embedment on soft clay seabed considering dynamic effect. The developed procedure will be useful for the calculation of seabed embedment in the early design stages (Pre-Front-End-Engineering-Design, Pre-FEED), and the procedure can be applied to check the design of on-bottom stability, free span, and many others. Briefly, this paper is organized into four sections. In this section, brief introduction and explanation were covered. In section 2, proposed procedure for estimating the pipe embedment is entered into details. In section 3, proposed method was proved by applied example and the obtained results from this study were summarized and concluded in last section.

2. Advanced procedure for estimation of pipe embedment

The procedures for estimating pipe embedment are shown in Fig. 2, including general method (i.e., rule-based approach) and proposed method based on DEF. In Fig. 2, the left-hand side represents the general method and the opposite side shows the proposed method. Once the embedment is obtained by the proposed method, it can be compared with embedment results calculated by existing design code (i.e., general method). If the embedment by proposed method is less than the results from the general method, dynamic installation analysis needs to be repeated.

The details of two approaches are covered in subsequent sub-sections, and the following method has been proven by applied simple examples in Section 3.

2.1 General method (General approach)

In the early stage of subsea pipeline Front-End-Engineering-Design (FEED), structural safety and reliability during operation period (design life) should be carefully checked and confirmed by engineers. Among good examples of design checklist in FEED for pipeline are on-bottom stability and free span length. Both design check lists are closely related with the amount of seabed embedment. Generally, in order to estimate seabed embedment, design code or rule-based calculation (so-called general method) is performed in current offshore industry (DNV 2006, 2010).

The basic concept of general approach is minimizing the lift force of pipeline, which means seabed embedment can be calculated based on the assumption of maximum pipe forces to seabed direction. The applied forces on the pipe may also be classified as submerged weight, lift force, and many others as shown in Fig. 3. This method can simply be applied to the pipeline FEED by using empirical formula, which assumes zero lift force in order to maximize subsea embedment. In addition, it considers that different types of submerged weight are assumed depending on conditions of pipe such as installation, operation, and system test.

In addition, the pipe condition is assumed as a shape that rests on the seabed along the pipeline length. In case of real installation condition, pipe structure will be installed with catenary shape as shown in Fig. 4. However, in general procedure, catenary shape is not considered and the shape only rests on the seabed condition applied to the design of pipeline. Briefly, the common steps of general method are presented below, and these steps could be equally applied to the proposed method.

- Definition of initial design input
- Definition of pipe shape (related to pipe condition)
- Definition of soil model
- Identification of reaction forces
- Estimation of pipe embedment

For the first step regarding calculation of subsea pipeline embedment, initial design input should be given such as pipe, soil, and internal fluid data. Once the initial design inputs are identified, pipe embedment can be easily calculated based on simple empirical formula developed by several test results including soil effect. However, empirical formula can only consider one type of pipe shape, which is the pipe that rests on seabed condition. This means that seabed reaction force is comprised of two parameters, which are submerged weight of pipe and its lift force. In addition, this empirical formula is barely suitable for soft clay type seabed. This is one of the important reason and background of the present study.

If the pipe is in system test condition (water filled condition) or operation condition (produced fluid filled condition), the vertical force of pipe is considered as the pipe submerged weight with internal fluid weight. The maximum pipe embedment is occurred when the maximum pipe submerged force is applied to the seabed among various pipe conditions. Therefore, general approach

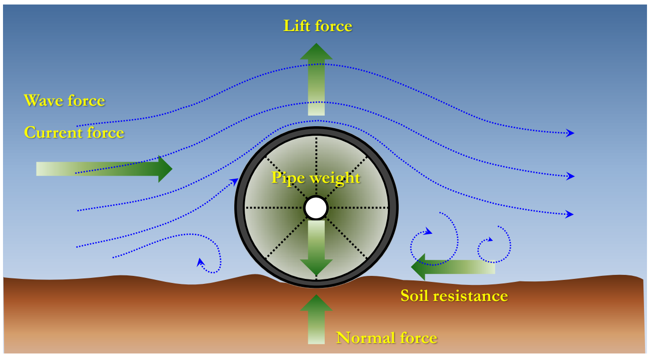


Fig. 3 Applied force of installed subsea pipeline

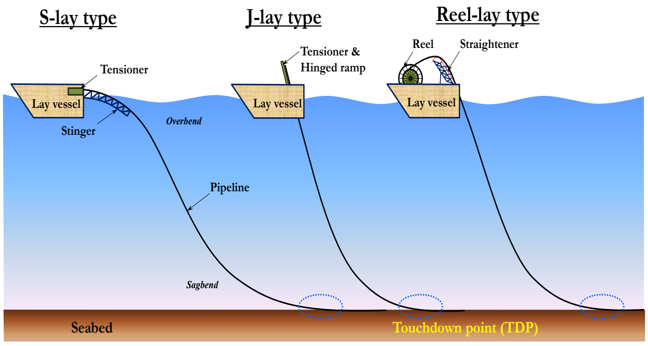


Fig. 4 Types of pipeline installation and its catenary shape

requires only two design inputs, i.e., basic pipe and soil data.

In addition, it cannot consider any type of dynamic effect that is normally applied to the installation of pipeline due to dynamic installation conditions by complex environmental loads. In this regard, advanced procedure for estimating seabed embedment is proposed based on dynamic embedment effect in the present study.

2.2 Advanced method (Proposed approach)

In case of the proposed concept that considers DEF as shown in right part of Fig. 2, it has more complex procedure, including four types of empirical curves illustrated in the most right side box with purple colour in Fig. 2. The core parameters related to the proposed method are presented in Eqs. (1) to (4). The details can be referred to Abbreviations & Nomenclatures section in the front page

$$W_{eff.} = \frac{W_s}{D \times S_u} \tag{1}$$

$$TLF = \frac{R_S}{W_s} \tag{2}$$

$$DLF = \frac{R_D}{R_S} \tag{3}$$

$$DEF = \frac{E_D}{E_S} \tag{4}$$

Four empirical formulas were developed using Eqs. (1) to (4) as shown in Fig. 2. The DLF versus DEF curve, which is derived in the last step, made possible the easy estimation of dynamic embedment. This procedure is proposed based on the relation between pipe embedment and seabed reaction force, including its static and dynamic phenomena. In general, pipe condition can be expressed as catenary shape when it is under installation shown in Fig. 4.

It is certain that the catenary shape of pipe can be changed depending on its installation method such as S-lay, J-lay, Reel-lay and others. In addition, various linear or nonlinear seabed soil models might be considered, such as rigid seabed, rigid plastic seabed, elasto-plastic model based constitutive equation based seabed models, and many others. Critical parameters, i.e., flexural stiffness (EI) and horizontal top tension (T_h) vary with the types of seabed soil model, which change vertical force distribution of pipe at touch-down zone (TDZ).

For this reason, nonlinear soil model is normally applied to the installation analysis of subsea pipeline with the effect of seabed embedment. Pipe embedment in static condition including laying configuration effect and touchdown lay factor (TLF) can be calculated through the static installation analysis. Once the static installation analysis is completed, two empirical formulas can be obtained as follows:

2.2.1 Development of effective pipe weight versus static embedment by pipe diameter curve (Step 1)

As a preliminary, relationship between effective pipe weight (W_{eff}) and static embedment by pipe diameter (E_S/D) is investigated. The effective pipe weight (W_{eff}) parameter is commonly adopted in both curves shown in the first and second steps which is shown in Fig. 2 with purple colour. It is composed of three variables of submerged pipe weight (W_s), pipe diameter (D), and shear strength of undrained seabed soil (S_u). The curve obtained from first step, known as W_{eff} versus E_S/D curve, will be compared to dynamic embedment results and used for the determination of final embedment at the final step in Fig. 2.

2.2.2 Development of effective pipe weight versus touchdown lay factor curve (Step 2)

At the second step, relationship between effective pipe weight (W_{eff}) and touchdown lay factor ($TLF=R_S/W_s$) is formularised. In case of the second curve, known as W_{eff} versus TLF curve, TLF is used as an indicator for the increased reaction force at touchdown point due to the stress concentration effects during the process of pipe installation. Although this TLF values normally lie between 2.0 and 3.0 (Bruton *et al.* 2006, Palmer 2008), additional parameters should also be considered with regard to laying conditions, i.e., lay tension, departure angle of pipe, bending stiffness and many others (Parmer 2008) in order to obtain accurate range of TLF. It is found that the well-fitted empirical formulas in the first and second steps could be obtained by static installation analysis.

In the present study, OrcaFlex numerical simulation code (OrcaFlex 2013) was applied to both of static and dynamic analysis. Other similar types of simulation codes may also be applied to this analysis. Once the static installation analysis has been completed through the numerical simulation, dynamic installation analysis is performed, and two more curves can be obtained from the following steps.

2.2.3 Development of effective pipe weight versus touchdown lay factor curve (Step 3)

At the third step, relationship between touchdown lay factor ($TLF=R_S/W_s$) and dynamic lay factor (DLF=a) can be achieved. Dynamic lay factor (DLF) and dynamic embedment factor (DEF) can be derived by dynamic installation analysis. DLF means the ratio between dynamic reaction force and static reaction force. The obtained TLF values by static analysis can be used as an input data for the development of the third curve, namely TLF versus DLF curve. This static result is connected by dynamic results through the TLF versus DLF curve.

2.2.4 Development of effective pipe weight versus touchdown lay factor curve (Step 4)

At the last step, relationship between dynamic lay factor ($DLF=R_D/R_s$) and dynamic embedment factor ($DEF=E_D/E_S$) is obtained. Finally, DEF can be estimated by DLF versus DEF curve, which can be derived in the final step. The amount of embedment from dynamic installation effect can be obtained by multiplying the estimated DEF by static embedment (E_S), which is obtained in the first step.

The comparison of seabed embedment between general and proposed method was performed once the dynamic installation embedment has been decided by the proposed method. In the process of comparison, iteration is required when the pipe embedment by the proposed method is smaller than the obtained embedment by the general method. In this case, the number of cycle should be increased for lateral movement of pipeline at touchdown point. Additional dynamic installation analysis can be performed based on the increased number of cycle of pipeline.

Finally, the pipe embedment was determined when the obtained embedment by dynamic installation analysis satisfies the guideline of comparison. This means that the obtained embedment by the proposed method is bigger than the result by the general method. The applicability of the proposed method is investigated by applied example in the next section.

3. Verification of proposed method by applied example

In the present section, verification work was performed to check the applicability of the proposed method. The general approach has been previously studied by Yu (2014), effect of nonlinear soil parameters on seabed embedment has also been performed by Yu *et al.* (2015). The proposed method part is mainly covered in this study. The comparison results are briefly illustrated in the last part. In briefly, three random seeds were selected to verify the applicability of proposed method with regard to estimation of dynamic embedment including dynamic environmental effects, such as irregular seastate, dynamic loads, and nonlinear soil properties. Once the design inputs are defined, static and dynamic installation analysis are performed to calculated pipe embedment based on proposed procedures in Fig. 2. The obtained embedment by DLF and DEF curve from proposed method was compared with general method. The details were explained in subsections.

3.1 Design input

The 32-inch pipeline data are summarized in Table 1. This pipeline is an export line to transport gas to the onshore refinery. In case of installation, pipe corrosion allowance is not considered and internal fluid is regarded as a void condition.

The pipeline is installed on very soft clay with shear strength of 2.1 kPa and the clayey soil is distributed throughout a 13 km distance. The basic soil data are summarized in Table 2.

The nonlinear hysteretic soil model by Randolph and Quiggin (2009) was adopted for applying advanced method to consider dynamic effect. For the nonlinear behaviour under pipe-soil interaction, required parameters are presented in Table 3. The values of nonlinear parameters are selected based on the recommendation range for soft clay (OrcaFlex 2013). The shear strength gradient is not considered and pipe interface is regarded as smooth condition.

Table 1 32-inch pipeline data

Description			Unit	Values
General data	Outer diameter		mm	813 (32-inch)
	Wall thickness		mm	20.6
	Material		-	Carbon steel
	Service		-	Dry gas
	Corrosion allowance		mm	1
	Fluid density		kg/m^3	107
Material	Pipe specification		-	API 5L X65
	Density		kg/m^3	7,850
	Young's modulus		MPa	207,000
	Poisson ratio		-	0.3
	SMYS		MPa	450
	SMTS		MPa	535
Coating	Corrosion	Thickness	mm	4.2
		Density	kg/m^3	940
	Concrete	Thickness	mm	95
		Density	kg/m^3	3,044

Note: SMYS = specified minimum yield strength (unit: MPa), SMTS = specified minimum tensile strength (unit: MPa)

Table 2 Soil (soft clay) data

Parameters	Unit	Values
Undrained shear strength	kPa	2.1
Submerged unit weight	kN/m^3	6.09
Bulk density	kN/m^3	16.15
Poisson's ratio	-	0.495

Table 3 Non-dimensioned parameters for nonlinear soil model

Parameters		Values
Penetration resistance factor	a	4.97
	b	0.23
Normalized maximum stiffness ($K_{\max}$)		150
Soil buoyancy factor (f_b)		1.33
Suction resistance ratio (f_{suc})		0.6
Normalized suction decay distance (λ_{suc})		0.3
Repenetarion offset after uplift (λ_{rep})		0.3

Three seeds in irregular sea states are summarized in Table 4. The direction of environmental loads, including wave and current to pipe axis laid on seabed, are shown in Fig. 5. For the realistic environmental condition, irregular sea states were used instead of regular wave sea states. In addition, the applied direction effect reduces the environmental load to pipeline on the seabed. The DEF is sensitive regarding environmental data. This approach is recommended because the DEF curve is drawn through dynamic reaction force under random irregular sea states. However, an in-depth study on pipe embedment by through

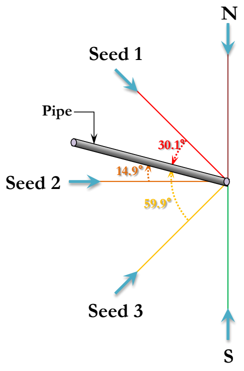


Fig. 5 Wave and current angle with regard to pipeline axis

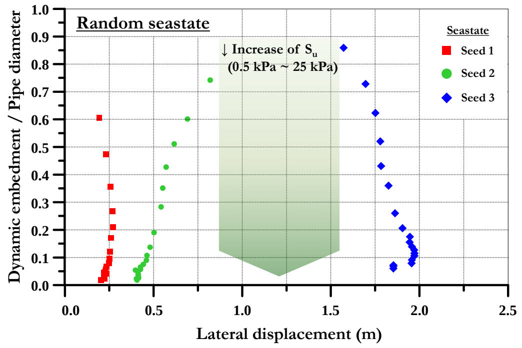


Fig. 6 Dynamic embedment by lateral displacement at touchdown zone under irregular seastates

Table 4 Environmental data (Yu 2014)

Irregular seastate	Seed 1	Seed 2	Seed 3
Wave height, H_s (m)	2.6	4.7	4.4
Peak period, T_p (s)	8.7	11	10.7
Current velocity (m/s)	0.83	0.33	0.35

various environmental conditions for more general DEF approach is required.

3.2 Pipeline Embedment based on general method

DNV (2010), "on-bottom stability design of submarine pipelines", uses the formula by Verley and Lund (1995) derived from various experiment results for the calculation of initial penetration depth. This formula deals with penetration resistance through model testing and is indicated in Eq. (5). However, this equation underestimates the penetration depth especially in soft clay, and results in very unrealistic submerged pipe weight

$$\frac{z_{pi}}{D} = 0.0071 \cdot \left(\frac{V}{D \cdot S_u} G_c^{0.3} \right)^{3.2} + 0.062 \cdot \left(\frac{V}{D \cdot S_u} G_c^{0.3} \right)^{0.7} \quad (5)$$

where, z_{pi}= initial penetration depth, D= pipeline diameter, V= vertical force per unit length, S_u= shear strength, $G_c = S_u / (D \cdot \gamma_s)$ = soil (clay) strength parameter, and γ_s = dry unit soil weight.

The pipe embedment results at a shear strength of 2.1 kPa from various conditions using the empirical formula are summarized in below Table 5.

3.3 Pipeline embedment based on proposed method

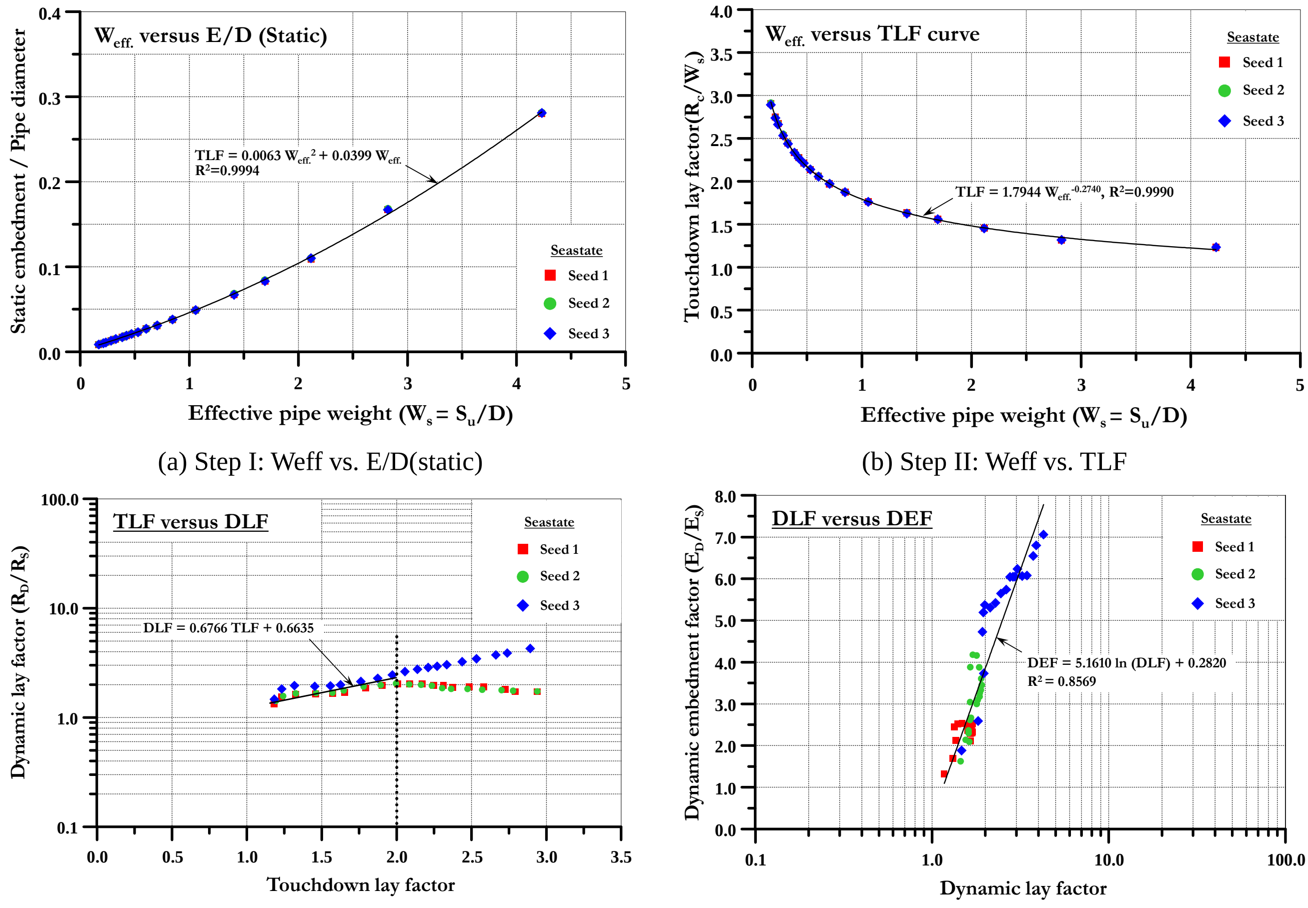
To calculate pipe embedment based on the advanced approach, the dynamic pipe embedment under random sea states with three seeds is calculated as shown in Fig. 6. Dynamic laying analysis was performed in the soft clay ranges of shear strength from 0.5 kPa to 25 kPa (DNV 2010). It was confirmed that the increase of shear strength at each sea state condition decrease the dynamic embedment. Furthermore, as the lateral displacement at TDZ increased, the pipe embedment increased at each shear strength value. The lateral displacement of the pipe at TDZ has a close relation with pipe embedment. As the lateral displacement gets larger due to pipe and vessel motion by environmental load, cyclic effects related to pipe embedment at TDZ shows a greater increase.

Table 5 Pipeline embedment at shear strength of 2.1 kPa by general method

Method	Empirical formula by Verlay and Lund (1995)		
Conditions	Installation (void)	Operation	System test
Embedment / D	0.07	0.08	0.21

Once static analysis has been done, dynamic analysis can be performed based on obtained results. Through dynamic analysis, the empirical formulas of DLF by TLF in Fig. 7(c) and DEF by DLF in Fig. 7(d) were obtained. As the relation between DLF and TLF had a nonlinear trend with TLF of 2.0, the results before TLF of 2.0 are recommended. This DLF and TLF relations are closely related to estimation of embedment. Currently, 4.0 value of dynamic embedment factor (DEF, dynamic embedment / static embedment) is normally suggested through research on pipe-soil interaction (Wang *et al.* 2009). In this regards, probabilistic approaches, i.e., Average case (mean value, M), Severe case (mean value + standard deviation, M+SD), and Slight case (mean value − standard deviation, M-SD) were adopted for consideration of nonlinear behaviour of dynamic phenomenon as shown in Fig. 8. It shows three examples of DLF versus TLF curves with 0.0 to 2.0 ranges of TLF, i.e., severe, average, and slight cases. In the present study, the values from Fig. 8 were used as an input for the final DEF curve in Fig. 7(d).

Finally, the dynamic embedment at shear strength of 2.1 kPa from the DEF curve by using the proposed approach was approximately 0.48 D of severe case, 0.39 D of average case, and 0.30 D of slight case, in respectively. The obtained embedments show reasonable result in comparison with field data of 0.56 D (Yu 2014) by Side Scan Sonar (SSS) as shown in Table 6. It is certain that this study only assumed limited number of scenarios, and further studies should be performed including more reliable scenarios in order to get high accurate values. In case of the general approach, 0.21 D of pipe embedment was obtained by empirical formula based on Verlay and Lund's approach



(a) Step I: Weff vs. E/D(static)

(b) Step II: Weff vs. TLF

(c) Step III: TLF versys DLF curve

(d) Step IV: DLF versus DEF curve

Fig. 7 Pipe embedment based on proposed method under irregular seastates (procedure can be referred to Fig. 2 and section 2.2)

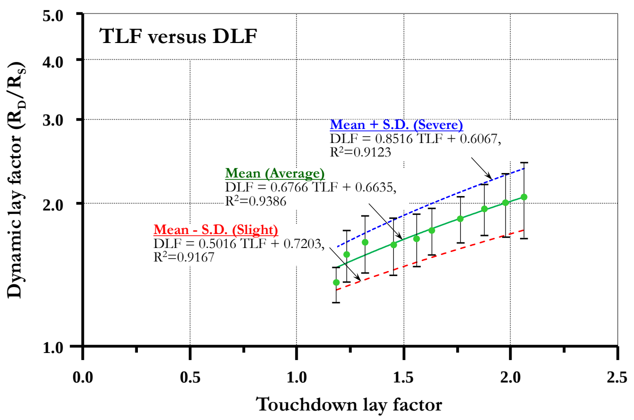


Fig. 8 Explanation of TLF versus DLF

(DNV 2010). Although this approach was analyzed with limited cases, this procedure could be helpful for dynamic embedment.

Based on the obtained results from this study, the proposed method can be applied to estimate realistic embedment of subsea pipeline on soft clay and it will be useful to understand behaviour of seabed embedment in association with offshore installation.

Table 6 Comparison of pipe embedment at shear strength of 2.1 kPa

Methods	Field data	General method	Proposed method		
	SSS	Verlay and Lund	Nonlinear hysteretic model		
Conditions	As-laid	System test	Installation		
Embedment / D	0.56 (Mean)	0.21	Severe	Average	Slight
			0.48	0.39	0.30

4. Conclusions

Dynamic embedment factor, which is the ratio of dynamic embedment divided by static embedment, is the representative of non-dimensioned factor by considering dynamic effects for pipe embedment. However, there are limit on a wide range of applications, depending on dynamic condition. In this paper, an advanced procedure for the estimation of dynamic embedment based on dynamic embedment factor was proposed. Examples with dynamic conditions of irregular sea states variation were performed to understand the approach with dynamic embedment factor.

DEF is a function of vessel speed, lay tension, pipeline

Table 7 Concept comparison of embedment calculation

Categories	Embedment estimation methods	
	General method	Proposed method
Pipe shape	Pipe resting on soil	As-laying pipeline on soil
Pipe condition	Installation or System test	Installation
Soil model	Empirical formula by Verley and Lund	Nonlinear hysteretic model
Maximum reaction force	Water-filled pipe submerged weight with zero lift force	Touchdown contact force by laying configuration and cyclic loading at TDP by vessel motion with lift force
Embedment	Initial embedment	Initial and dynamic laying embedment

configuration and environmental loading during installation. It means that DEF curve has impacts on various parameters under dynamic installation condition. However, only the procedure for the estimation of dynamic pipe embedment is focused in this study because DEF is a good indicator for dynamic embedment. From the examples based on the proposed method, many uncertainties for dynamic embedment can be reduced, and the understanding on the estimation of dynamic embedment, which is not known prior to installation in field, can be improved.

Finally, a number of additional verification works should also be performed for further study. Basic concept of applied method for calculation of seabed embedment is summarized in Table 7.

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Abbreviations & Nomenclatures

D	=	Pipe outer diameter
TDZ	=	Touchdown zone
TLF	=	Touchdown lay factor
DLF	=	Dynamic reaction force
DEF	=	Dynamic embedment factor
FEED	=	Front end engineering design
E_D	=	Dynamic embedment
E_S	=	Static embedment
R_D	=	Dynamic reaction force
R_S	=	Static reaction force
S_u	=	Undrained shear strength of soil
T_h	=	Horizontal top tension
$W_{eff.}$	=	Effective pipe weight
W_s	=	Pipe submerged weight