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Back-Analysis of Deep Embedment of a Heavy Pipeline in Very Soft Clay

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ABSTRACT: Pipe-soil interaction forces are key elements in the design of offshore pipelines in very soft clays. These forces are highly influenced by the pipeline as-laid embedment. It is therefore important to accurately predict the range of embedments in the field, in order to bracket the interaction forces to consider in design to satisfy all limit states. Although methodologies exist, uncertainties remain when making these predictions. A major uncertainty relates to the approach to adopt, and the level of soil remoulding to consider, to account for dynamic lay effects, when dealing with heavy pipelines in very soft clays for which large embedments are anticipated. A back-analysis of the embedment of a heavy pipeline in very soft clay is presented and comparisons are made with common design methodologies. The objective of the back-analysis was to use the outcomes in future pipeline designs at the site. The pipeline as-laid survey has confirmed that the embedment was large. A second survey has revealed that further embedment took place over a period of 2 years, which was unexpected. The main outcomes of the back-analysis are presented. In particular, the methodology and level of soil remoulding to consider to match the observed embedment is discussed. Regarding the increase of embedment, two plausible hypotheses are discussed.

Keywords: pipelines, embedment, pipe-soil interaction, very soft clay, back-analysis

1 INTRODUCTION

Axial and lateral pipe-soil interaction forces are key elements in the design of offshore high pressure, high temperature (HPHT) surface-laid pipelines in very soft clays. The consideration of low and high estimates of pipe-soil interaction forces is generally required during design to satisfy all limit states. These forces are highly influenced by the pipeline as-laid embedment. It is therefore important to predict the range of expected as-laid embedments in the field, in order to accurately and reliably bracket the interaction forces that should be considered in design.

A common approach to assess pipeline embedment in very soft clays is the one developed as part of the SAFEBUCK Joint Industry Project (JIP), now incorporated into DNV-RP-F114 (2021). The recommended equations and parameters are based on theoretical solutions for pipe embedment (z) up to half of the outer pipe diameter (D). Therefore, the method is not strictly applicable for large embedments, as can be encountered for heavy pipelines in very soft clays.

SAFEBUCK methodology also recommends that analyses use the remoulded undrained shear strength at the pipe invert to account for soil disturbance from vertical and horizontal pipe movements during laying. This is a convenient proxy to account for dynamic lay affects that are complex to quantify. This approach has shown to provide satisfactory results for shallowly embedded pipelines, but uncertainties remain for deeply embedded heavy pipelines. As the embedment increases, the pipeline motions are restrained by the lateral soil resistance and the pipeline engages deeper intact soil. Therefore, the assumption of full remoulding in this case is questionable and may lead to unrealistically large pipeline embedment.

This paper presents a back-analysis of the deep embedment of a heavy pipeline in very soft clay. The pipeline as-laid survey done shortly after installation has revealed that the embedment was indeed large. The SAFEBUCK methodology is compared with the deep embedment models proposed by Martin and White (2012) and Tho et al (2012) to verify how these models perform in this particular case. The “apparent” soil remoulding that should be considered to match the observed deep embedment is also discussed.

An Out-Of-Straightness (OOS) survey was performed 2 years later and has revealed that further embedment took place, which was unexpected. Two hypotheses that could explain the observed evolution of embedment with time are discussed in this paper.

The objective of the back-analysis was to use the outcomes and improve the embedment predictions for future pipelines planned at the site. Pipeline survey and monitoring data is often an under-utilized resource (White et al, 2015). However, these field data provide invaluable information given the uncertainties related to the prediction of pipeline embedment.

2 FIELD OBSERVATION DATA

2.1 Seabed properties

The seabed soil conditions consist of an extremely low strength calcareous silica clay of extremely high plasticity. The water content is very high at mudline, decreasing with depth. In terms of grain size, the clay is very silty (25-40% silt content) and slightly sandy (0-10% sand content). The clay is organic in the first half meter, then becoming slightly organic. The main soil properties are summarized in Table 1.

In addition to conventional cone penetration and laboratory tests, mini T-bar tests were performed in box cores to define more accurately the strength profile at shallow depth. Monotonic and cyclic mini T-bar tests were performed to assess the intact and remoulded undrained shear strengths. The design undrained shear strength profiles were assumed to be bilinear, increasing with depth with a changing gradient at 0.1 m depth. The design remoulded undrained shear strength profiles were obtained by dividing the design intact strength values by the best estimate (BE) sensitivity and were observed to match well the remoulded strength data, which included results from fall cone, laboratory vane and cyclic mini T-bar tests (after 20 to 25 cycles) (Figure 1).

Table 1. Soil properties.

Parameter	**Depth [m]**	**Value LE**	**BE**	**HE**
Water content [%]	0 – 1.5	80	-	280
Plasticity index [%]	0 – 1.5	85	-	140
Unit weight [kN/m3]	0 – 1.5	11.5	12.4	14
Intact undrained shear strength [kPa]	0	0	0.3	0.7
	0.1	0.5	1	1.8
	1.5	2	3.1	4.5
Remoulded undrained shear strength [kPa]	0	0	0.1	0.2
	0.1	0.15	0.3	0.5
	1.5	0.6	0.9	1.3
Sensitivity [-]	0 – 1.5	2	3.4	4.8

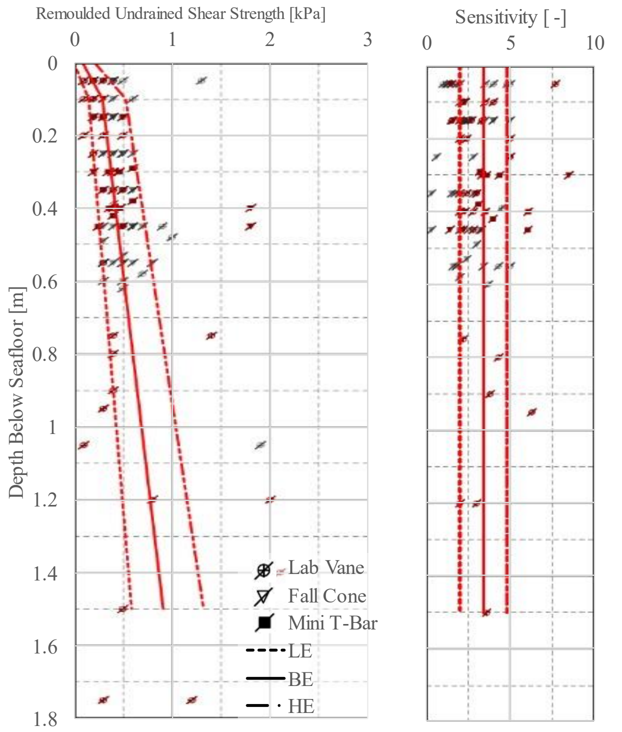

Figure 1. Remoulded undrained shear strength and sensitivity profiles – laboratory data and design lines.

2.2 Pipeline properties

The 12” production flowline needed to be insulated to satisfy the flow assurance requirements. The combination of two thermal concepts – Wet Insulated (WI) and Pipe-In-Pipe (PIP) – was considered resulting in two pipeline configurations. The main pipeline properties are provided in Table 2. The PIP is significantly heavier than the WI and has a higher flexural rigidity.

Table 2. Pipeline properties.

Pipeline property	**WI**	**PIP**
Outer diameter D [m]	0.486	0.413
Submerged empty weight [kN/m]	1.152	2.814
Submerged flooded weight [kN/m]	1.687	3.349
Submerged operational weight [kN/m]	1.298	2.960
Flexural rigidity [kNm²]	63738	140830

The pipeline was installed in empty conditions. The project’s construction schedule was such that, almost two years elapsed between pipeline installation and flooding. The pipeline remained empty on the seabed during that period. An as-laid pipeline survey was performed just after pipeline installation. An Out Of Straightness (OOS) survey was performed as part of the pipeline thermal performance test (two years after the as-laid survey) before the pipeline commissioning. The pipeline flooding took place before the OSS survey, i.e. between the two surveys.

2.3 Observed pipeline embedment

The pipeline penetration was measured at least every meter along the pipeline. These measurements are smoothed using a moving average of 50m. The average of the left and right measurements at a lateral distance of 3m gives a reasonable estimate of the observed nominal pipeline penetration.

The two pipeline sections of interest are defined based on pipeline properties (WI and PIP) discussed above. The 3-sigma rule is applied to filter out outliers from the surveyed data. A normal distribution is assumed to compute a lower and an upper bound for the error range, corresponding to the 10^{th} and 90^{th} percentile of probability respectively.

Figure 2 and Figure 3 show the probability distribution function and cumulative distribution function of the WI and PIP pipeline sections embedment respectively, as laid and OOS.

2.3.1 As-laid embedment

As summarized in Table 3, the WI pipeline embedment ratio z/D varies between 0.47 and 1.07, with an average value of 0.77. The PIP pipeline embedment ratio z/D varies between 1.25 and 1.80, with an average value of 1.53.

2.3.2 OOS embedment

As summarized in Table 3, the WI pipeline embedment ratio z/D varies between 0.78 and 1.31, with an average value of 1.04. The PIP pipeline embedment ratio z/D varies between 1.49 and 2.40, with an average value of 1.95. There is an evident increase of pipeline embedment between the two surveys, with the average embedment ratio increasing from 0.77 to 1.04 for the WI pipeline, and from 1.53 to 1.95 for the PIP pipeline.

Table 3. Embedment surveys summary (low/high estimate values for 80% confidence interval).

Embedment ratio [z/D]	**WI**		**PIP**	
	As-laid	OOS	As-laid	OOS
Average	0.77	1.04	1.53	1.95
Std. deviation	0.23	0.21	0.22	0.36
Low estimate	0.47	0.78	1.25	1.49
High Estimate	1.07	1.31	1.80	2.40

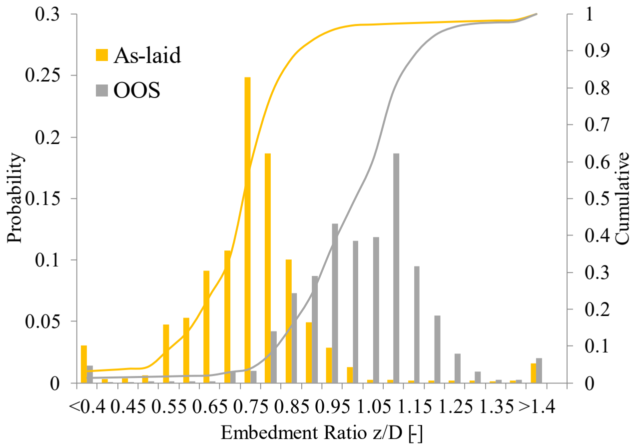

Figure 2. Probability distribution of wet insulated (WI) pipeline embedment (as-laid and OOS).

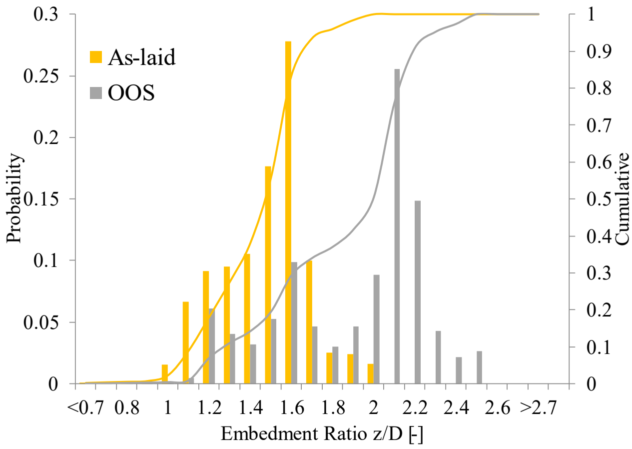

Figure 3. Probability distribution of pipe-in-pipe (PIP) pipeline embedment (as-laid and OOS).

3 BACK-ANALYSIS OF PIPELINE EMBEMDENT

3.1 Comparison with deep embedment models

The equations and parameters proposed in SAFEBUCK are based on theoretical solutions for pipe embedment (z) up to half of the outer pipe diameter (D) (that is, z/D < 0.5). The method also proposes an enhanced buoyancy due to heave with the factor f_b = 1.5, which is also only valid for shallow embedments. A comparison is thus made with deep embedment models such as those proposed by Martin and White (2012) and Tho et al (2012). For that comparison the heave factor f_b is assumed to reduce from 1.5 to 1.0 as the embedment increases from z/D = 0.5 to 1.0, as suggested by Bruton (2014).

Martin and White (2012) performed parametric wished-in-place finite-element limit analyses for deep embedments till z/D = 5. They produced results using non-dimensional variables (i.e. V/s_uD versus z/D) for soils with different weight ratios γ'D/s_u and for smooth and rough interface behaviour.

Tho et al (2012) performed large deformation finite elements analyses of the pipeline penetration process till large penetrations. These are considered to be more realistic than the Martin and White (2012) results, which are obtained from wished-in-place simulations, as they capture the trench formation above the pipeline, which influences the vertical soil resistance and has been observed to depend on the ratio s_u/γ'D.

The load-penetration curves obtained with the different models using the LE and HE soil parameters are compared on Figure 4 and Figure 5 for the WI and PIP pipeline sections respectively. In this comparison, the fully remoulded strength is considered to account for dynamic lay effects, as recommended by SAFEBUCK. For each model, the range of predicted embedment for the two pipelines can be deduced considering their submerged empty weights. In this particular case, there was no stress concentration at the touch down point (f_{lay} = 1.0) so the vertical load corresponds to the static weight of the pipeline. The observed pipelines as-laid and OOS embedments are also presented as a comparison.

The analysed methods give comparable results in this particular case. The variations do not have a significant influence on the main conclusion regarding the range of expected pipeline embedment using low estimate (LE) and high estimate (HE) soil parameters. Therefore, model selection is of lesser importance in this case, making SAFEBUCK a suitable choice.

The observed embedment of WI pipeline suggests LE soil parameters apply, and full remoulding of the soil.

The observed embedment for PIP pipeline suggests HE parameters, which contradicts the findings for WI. If for the sake of consistency, LE soil parameters and full remoulding is assumed, the embedment analysis yields very large embedments. The soil being the same for WI and PIP, full remoulding is the assumption that most likely needs to be revisited for PIP.

3.2 Apparent degree of remoulding

There is evidence of partial remoulding in PIP, likely caused by the large embedment, resulting in more lateral restraint of the pipeline beyond z/D=0.5 and reduced dynamic lay affects. However, full remoulding for WI was observed despite similarly large (though somewhat lower) embedment. A factor contributing to the observed partial remoulding for the PIP might be its higher flexural rigidity, possibly reducing pipeline motions and dynamic lay effects compared to WI.

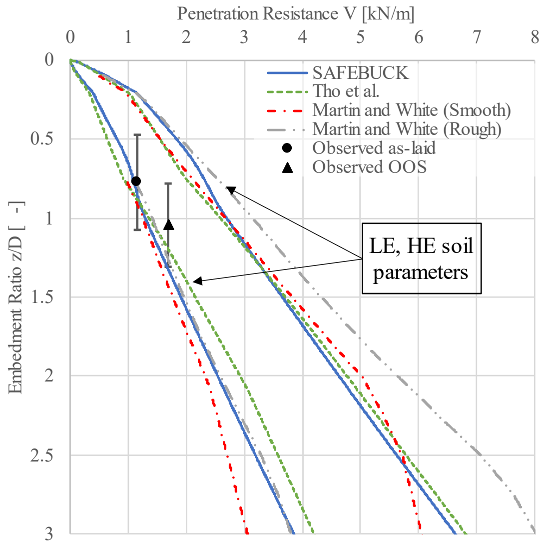

Figure 4. Comparison of penetration resistance with respect to embedment ratio for wet insulated (WI) pipeline.

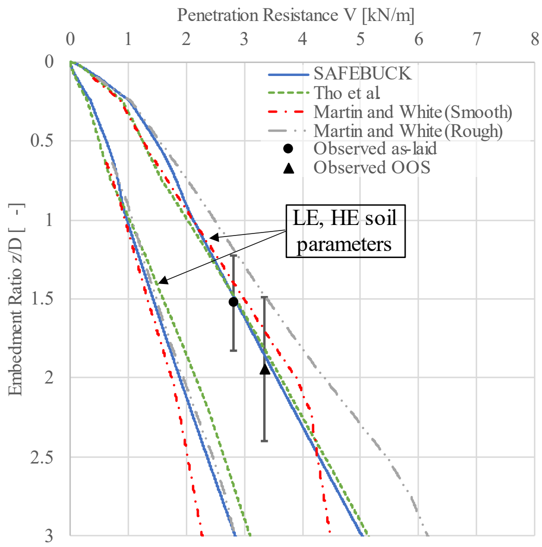

Figure 5. Comparison of penetration resistance with respect to embedment ratio for pipe-in-pipe (PIP) pipeline.

Using equation (1), a partial remoulding of 33% is back-calculated based on the observed embedment, and assuming LE soil parameters (Figure 6). It is noted that the assumed degree of remoulding has a significant impact on the predicted embedment.

$$Deg.\ Rem. = \frac{s_u - s_{u,pr}}{s_u - s_{u,r}} \times 100\% \qquad (1)$$

where $Deg.\ Rem.$ (%) is the degree of remoulding, s_u (kPa) is the intact undrained shear strength, $s_{u,r}$ (kPa) is the fully remoulded undrained shear strength,
$s_{u,pr}$ (kPa) is the partially remoulded undrained shear strength.

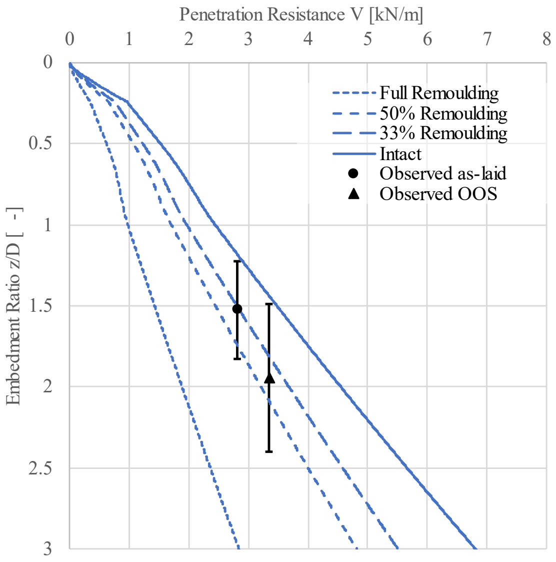

Figure 6. Penetration resistance with respect to embedment ratio for pipe-in-pipe (PIP) pipeline considering different degrees of remoulding.

3.3 Increase of pipeline embedment with time

The first hypothesis to explain the increase of embedment with time is that the clay did not reconsolidate between the installation and the hydrotest. However, it seems unlikely that the consolidation was not complete after a period of two years given the clay consolidation properties and relatively short draining path. Therefore, it would mean it did not regain strength through consolidation due to some kind of 'structure'. In this case, the remoulded (or partially remoulded) strength would be mobilised when the vertical load increases at flooding, generating additional embedment. The increase of vertical load at flooding is compatible with the observed increase of pipeline embedment, as observed on Figure 4, Figure 5 and Figure 6, which makes it a plausible scenario.

Another possible explanation for the observed increase of pipeline embedment is the compressibility of the clay under pipeline weight due to primary and secondary (creep) consolidation over the period between the two surveys. Consolidation settlement is generally not accounted for in pipeline design. However, Chatterjee et al (2012) have shown through large deformation finite element analyses that consolidation settlement can be significant for heavy pipelines in very soft clays.

A simplified settlement assesment is made with Plaxis to verify the order of magnitude, assuming normally-consolidated soil conditions and drained behaviour (corresponding to the end of primary consolidation), and ignoring creep deformations. A compression ratio $C_c/1+e_0=0.3$ is assumed in line with oedometer tests results performed at deeper depth and main soil properties summarized in Table 1. The model is 2D plane-strain and only half of the problem is modeled given the axis of symmetry (Figure 7). The results are summarized in Table 4.

Table 4. Comparison between calculated and observed increase of pipeline embedment.

Embedment increase [z/D]	**WI**		**PIP**	
	Empty	Flooded	Empty	Flooded
Calculated	0.04	0.09	0.29	0.39
Observed	0.27		0.42	

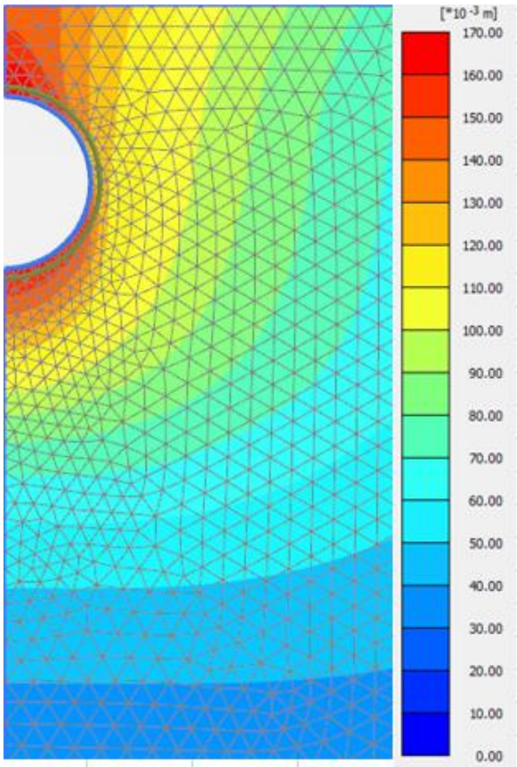

Figure 7. Calculated increase of pipe embedment for pipe-in-pipe under flooded conditions (PIP)

The calculated embedment is underestimated compared to the observed increase of pipeline embedment for the WI pipeline. However, calculated and observed embedments are more in line for the PIP.

The reality is obviously more complex. The assumption of normally-consolidated conditions in the remoulded soil just below the pipeline is probably justified on account that the stress history has been erased by the installation effects. However, further away from the pipe, the intact soil is slightly over-consolidated. One important factor in this particular case in the authors' opinion, is that the applied pressure from the pipeline brought back the clay to normally-consolidated conditions, due to the combination of heavy pipe weight and only very slight overconsolidation. In that state, the soil can undergo secondary (creep) consolidation. It is believed that these compressibility effects have not been given enough consideration in practice.

Another element that might have contributed to the increase of embedment with time is that the stress-concentration factor k_{lay} during installation has been assessed to be lower than 1.0 or around 1.0. That means that the pipeline was not over-embedded and the pipeline weight was in equilibrium with the bearing capacity of the soil after installation. This is a state in the soil for which shear creep strain could be generated.

The increase of pipeline embedment with time might also be due to a combination of several of the factors described above.

4 CONCLUSIONS

This back-analysis study compared the observed embedment of a heavy pipeline in very soft clay with common design methodologies and investigated the reasons behind the unexpected evolution of pipeline embedment over time.

The analysed methods to predict pipeline embedment gave comparable results in this particular case. The variations between methods did not have a significant influence on the main conclusion regarding the range of expected pipeline embedment using low estimate (LE) and high estimate (HE) soil parameters. Therefore, model selection was of lesser importance in this case, making the standard SAFEBUCK approach a suitable choice.

The assumption that dynamic effects during pipeline laying lead to full remoulding of the soil did not seem adequate for all considered cases. While the $S_{t,BE}$ (full remoulding) assumption was appropriate for the Wet Insulated Pipe (WIP), it was found that partial remoulding for the Pipe-In-Pipe (PIP) configuration was more adequate. The larger flexural rigidity of the PIP likely reduces dynamic effects and soil remoulding.

Two main hypotheses were proposed to explain the observed increase in embedment between installation and flooding. The first hypothesis suggests that additional penetration was induced by the weight increase during flooding, which could only occur if the soil consolidation was incomplete or if the clay did not regain strength through consolidation due to some kind of ‘structure’. However, the incomplete consolidation seems unlikely given the two-year period between surveys.

The second hypothesis is that the clay soil units underwent primary and secondary consolidation under the weight of the pipeline during the period between the two surveys. The pipeline's applied pressure likely brought the soil back to normally consolidated conditions, leading to primary and secondary (creep) deformations. Additionally, the lay factor k_{lay} during installation being close to 1.0 (indicating no stress concentration) suggests that the pipeline was not over-embedded and thus susceptible to shear creep strain.

In conclusion, the study highlights the importance of performing back-analysis given the uncertainties related to the prediction of pipeline embedment and its importance in the design process. The findings can inform future pipeline designs and improve the accuracy of embedment predictions.

AUTHOR CONTRIBUTION STATEMENT

JC Ballard: Conceptualiztion, Formal Analysis, Investigation, Visualization, Writing – Original Draft. **F Nader**: Formal Analysis, Visualization, Writing – Original Draft. **R Wallerand**: Validation, Writing – Reviewing and Editing.

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