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A risk based assessment of the punch-through potential of jack-up barges

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ABSTRACT

Our Client undertook a series of nearshore ground investigations for a development in the North West Shelf region of Western Australia. The ground investigations were undertaken between 2009 and 2012 using jack-up barges in water of up to 25 m depth. During the 2010 campaign a punch-through incident occurred in which equipment and samples were lost overboard.

A punch-through is the situation whereby one or more legs of the jack-up barge penetrate into the seabed without warning, having previously been supported. This can occur either during the jacking procedure or whilst at working height.

Following the incident, the Client wished to mitigate the risk of further punch-through incidents. We were engaged to develop a method of assessing the risk of punch-through across the site based on geological, geophysical and geotechnical information. The assessment was used to support the 2011 and 2012 nearshore ground investigation campaigns.

Our work involved the back analysis of the punch-though incident, the derivation of a geological model for the site, an assessment of the risk of punch-through over the whole site, and the development of an interactive tool which presented location specific assessment results and operational procedures. As new site investigation information was obtained it was imported into the assessment, to improve its accuracy. The results of the assessment were also used by the Client to influence the investigation programme.

This paper presents Arup's work. The punch-through assessment project is confidential. It is a condition of submission that the Client and the project location cannot be disclosed.

Keywords: Punch-through, Risk, Risk assessment, Jack-up Barge, Calcarenite

1 INTRODUCTION

A proposed Liquefied Natural Gas (LNG) development will process products recovered from the offshore North West Australia region. Preparatory work for the development involved on-shore and near-shore development components. The nearshore study site within the overall development was of approximately 50 km^2 area.

Four campaigns of nearshore site investigation were completed in support of the development. The investigations occurred between 2009 and 2012, and included intrusive investigations undertaken using jack-up barges (JUBs) in water of up to 25 m depth. Little previous investigation had been completed in the area.

Punching through is a known hazard to jack-up barge operations. The Maersk Victory jack-up barge punch-through (MESA, 1997) is a good example within the Australia region illustrating this risk.

Traditional methods of assessing the risk involve either the assumption of ground conditions, or case-by-case assessment in the field.

Following a punch-through incident during the 2010 investigation campaign, changes were implemented to mitigate the risk of further punch-through incidents in subsequent campaigns. This paper presents one component of these changes; the development of a risk based approach to assessing punch-through potential.

The approach comprised several phases. Initially the punch-through incident was back-analysed, and a relationship was developed between ground conditions and punch-through risk. A method was then developed by which the relationship could be projected over the entire site. The results were packaged into an interactive tool which was used to influence the investigation strategy, and to assess risk in the field.

2 PUNCH-THROUGH

A punch-through is defined as the situation whereby:

i. The JUB legs are loaded or are in the process of being loaded (i.e. the JUB is being jacked up, or is at working height). The legs rest on seabed material that is strong enough to support them, but which is underlain by weaker material;
ii. The supporting material fails beneath one or more legs, causing any affected legs to penetrate further into the seabed, often suddenly;
iii. The JUB may list or otherwise become unstable.

Two incidents occurred during the 2010 nearshore site investigation campaign. The first was described as an abnormal penetration incident, whereby one of the JUB legs penetrated 4 m further than the others during jacking. This incident did not affect the works.

The second incident was a punch-through incident. The JUB had been jacked-up for approximately 12 hours when one of its legs sank approximately 4 m into the sea bed without warning. This caused the JUB to list so that its bow was at the waterline. Equipment and samples were lost overboard, and personnel sustained minor injuries. The incident was classified by the Client as a high potential incident.

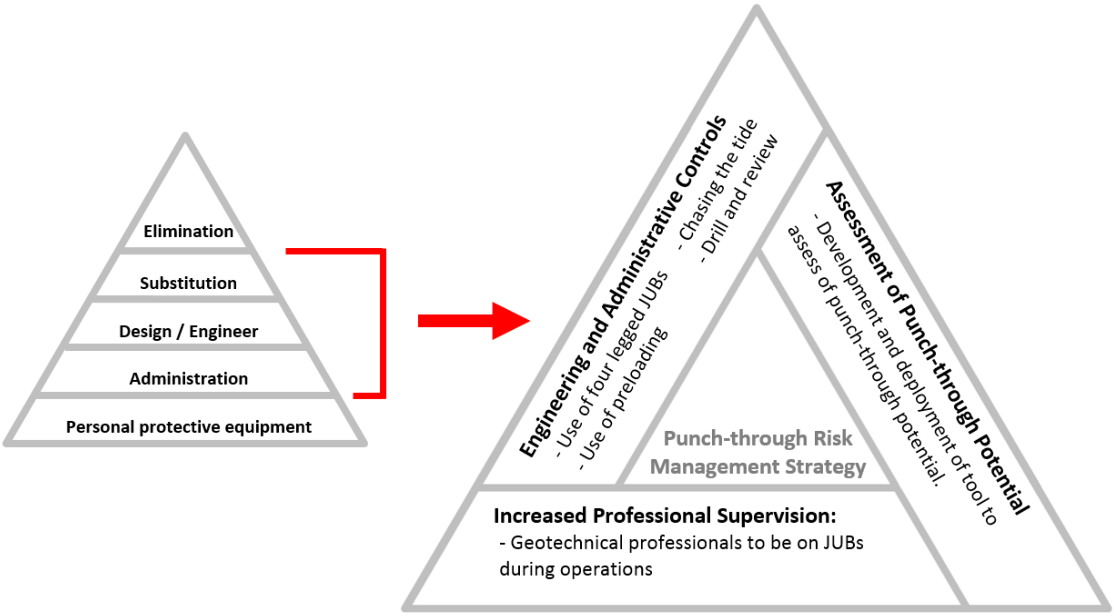


Figure 1. Risk controls and risk management strategy

Following the 2010 incidents the Client revised their risk management strategy and introduced additional risk controls. The aim of the risk management strategy was to ensure that the risk of punch-through was reduced to a level deemed to be as low as practically possible – a common industry aim. The strategy comprised three control areas, which when implemented together would reduce the risk of punch-through. The control areas were derived following consideration of the commonly adopted hierarchy of risk controls. The hierarchy of risk controls and the three control areas adopted are shown on the left and right of Figure 1 respectively. The Assessment of Punch-through Potential was one of the three areas of control.

3 GROUND CONDITIONS

Little previous ground investigation had been undertaken at the site. By the date of commencement of work on the Assessment of Punch-through Potential, ground investigation information obtained during the early campaigns was available.

Intrusive investigation information available comprised borehole and Cone Penetration Test (CPT) logs. CPT and boreholes were usually undertaken in complementary pairs at locations less than 5 m apart. Geophysical investigations including a Seismic Refraction Survey and an Ultra High Resolution Seismic Survey were completed as part of the early ground investigation campaigns. The geophysical information provided detailed sea-bed contours and a three-dimensional representation of the sub-surface geology. Aerial photography also permitted additional assessment of the shoreline geology.

The results of Uniaxial Compressive Strength (UCS) testing and Point Load testing on intact samples of Calcarenite allowed the characterisation of the strength of the material. It was noted that generally testing was undertaken on intact core samples, possibly skewing the strength results towards stronger materials. All strength test results were therefore correlated to sample quality and strength notations recorded on borehole logs, and to strength results recorded in CPT results. This permitted the derivation of a relationship between lower bound logged strengths, q_c (CPT cone strength) and UCS over the range of AS 1726 (Standards Australia, 1993) soil strength descriptions.

The ground model for the site was built up through interpretation of the various information sources. The nearshore geology of the region in which the study was based generally comprises Marine sands, underlain by Calcarenite, underlain by Pindan sands, as described in Table 1.

Calcarenite is commonly encountered on Australia's northwest shelf, and is described as a cemented material comprising sand and greater than 50% calcium carbonate. The strength and thickness of Calcarenite is known to vary significantly, and depends on the carbonate content, degree of cementation, and the impact of weathering.

Table 1: Ground conditions

Material	**Description**
Marine Sands	A loose sand layer, up to 5 m thick but generally <2 m thick.
Calcarenite	A cemented material comprising sand and >50% calcium carbonate. Thicknesses vary between 0 and 8.0 m, but are generally between 0.1 and 2 m.
Pindan Sands	A material comprising layers of loose sands, soft clays and dense silts. This is the soft material generally encountered beneath the Calcarenite.

4 BACK-ANALYSIS

The first stage of the project comprised the back analysis of the 2010 punch-through incident. During the early campaigns the JUB legs did not have spudcans attached, and were used as configured in Figure 2. The ends of the legs were broadly conical, with a 240 mm diameter sphere at the tip.

An attempt was made to use the SNAME guidelines (SNAME, 2002) to calculate the bearing capacity of two and three layered systems. These guidelines present procedures for assessing the stability and penetration of JUB footings. Having reviewed the calculations it was decided that using this method introduced too many assumptions to be of practical use in this situation. In particular, the method is designed for stronger clay or sand layers underlain by weaker clay layers, and it does not sufficiently address the characteristics of carbonates. Since the material on which the JUB legs were likely to rest was a highly variable rock, it was considered appropriate to take an alternative approach.
It was assumed that the ground conditions presenting a risk of punch-through would be similar to those at the location of the punch-through incident. As such, the most likely ground condition scenario at punch-through was Calcarenite underlain by a softer material (Pindan sands), ignoring the thin layer of Marine sand.

Figure 2. Jack-up barge leg configuration (Image © Client)

It was then assumed that the system was in equilibrium immediately prior to the 2010 punch-through incident, and therefore that the Factor of Safety (FoS) against punch-through was 1.0 at this time. This is justified by the fact that the JUB was stable on the location for some 12 hours prior to the punch-through.

The assumption of equilibrium permitted the derivation of an expression linking the strength and thickness of the Calcarenite and the size and weight of the JUB leg, whilst assigning a generic strength for the soft material beneath the Calcarenite. The expression derived is:

$$P = \tau_f \pi d f + N_c s_u A$$

The parameters are defined in Table 2.

Table 2: Punch-through assessment parameters

Parameter	**Description**	**Unit**
P	Leg load	kN
τ_f	Shear strength of Calcarenite	kPa
d	Diameter (effective) of leg	m
f	Depth to soft layer	m
N_c	Bearing capacity factor	-
s_u	Shear strength of soft layer	kPa
A	Cross sectional area (effective) of leg	m^2

The expression assumes that a plug failure of the same diameter as the leg will occur in the rock. A contribution to bearing capacity by the underlying soft layer is added to the plug capacity.

Effective (flat ended) leg diameters and leg pre-load weights were calculated for each JUB, as required by the expression. The expression was then validated by conducting sensitivity studies and assessing other borehole locations.

Code was developed that would calculate a weighted average UCS based on the strength descriptions and thicknesses of logged Calcarenite sub-layers as obtained from borehole logs. Lower bound strength values for each strength description were taken from AS 1726 (Standards Australia, 1993), and correlated with our experience of similar materials.

The shear strength of the Calcarenite back calculated using the above expression was compared to the shear strength derived using CPT data, and found to be consistent. The leg diameter at equilibrium using the cone strength data was back calculated and compared to the effective leg diameter; they were also found to be comparable.

Having derived the expression relating Calcarenite properties and JUB properties it was possible to assess the bearing capacity and FoS against punch-through for any given combination of Calcarenite strength and thickness.

5 THE ASSESSMENT OF PUNCH-THROUGH POTENTIAL

5.1 GEOLOGICAL MODEL

A three-dimensional geological model of the site was created using GIS. The model was defined through interpretation of all of the available geotechnical, geological, and geophysical information. The model was built in such a way that it would be possible to update it with the addition of future ground investigation information.

Within the geological model the site was split into domains of similar geological properties based on the geologists' interpretation of the available information. Interpreted default values of calcarenite thickness and strength were established for each domain.

An assessment of confidence in the geological definition of each domain was undertaken as part of the interpretation, based on the amount of ground investigation undertaken within the domain. It was of critical importance that the confidence rating was considered when understanding the geological definition and the results of the punch-through assessment for each domain.

Where sufficient site investigation information was present, isopachs (surfaces) of calcarenite thickness and surface reduced level were generated by using interpolation functions between known points. The geological domains are shown in Figure 3.

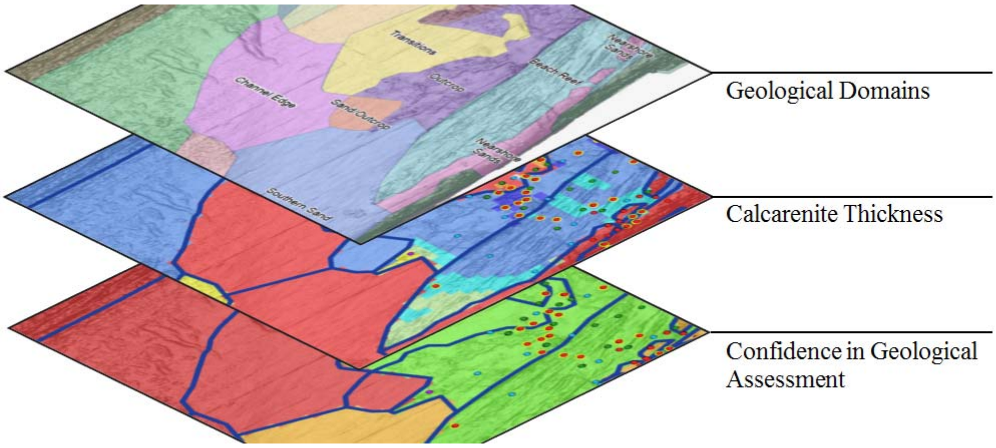


Figure 3. Geological model

Within the geological model the site was discretised into 5100 sample points on a 100 m square grid, the properties of which could be exported to a data file from GIS. The data file provided the inputs to the Punch-through Assessment Program.

5.2 PUNCH-THROUGH ASSESSMENT PROGRAM

A punch-through assessment program was created for this study. The program is able to process the data file from the geological model, taking in Calcarenite thickness and strength values at each sample point, and calculating the allowable bearing capacity and FoS against punch-through across the site for a specific JUB.

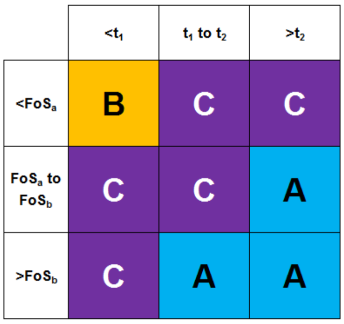
As the calculations are being completed, the tool tracks the average and the range of the Calcarenite thickness and FoS values within each domain. Based on the comparison of these values to boundary values, domains are then assigned to one of three groups, A, B or C, as defined in the matrix in Figure 4. The three groups correspond to the three likely scenarios for punch-through, also defined in Figure 4.

The assignment of groups based on Calcarenite thickness and FoS implicitly assigns greater influence to thickness than to strength. This is because thickness is an input variable in the FoS calculation. This method therefore principally assigns domains to groups based on thickness, but allows for the influence of strength. This approach was considered to be justifiably conservative, given the variability of the strength and thickness of the Calcarenite and the investigative nature of the works.

The assessment tool writes the results of the assessment back into the data file for visualisation in GIS, and also writes the results into the interactive flow charts described below.

The automation of the assessment made it easily and quickly repeatable. This allowed it to be repeated regularly as information was returned from site and incorporated into the geological model.

Group	**Definition of Group**
🟦 **A** (Thicker)	Thicker Calcarenite likely to be present, on which the JUB is likely to rest. Karstic features (cavities) within the Calcarenite may result in unpredictable penetrations. Calcarenite thickness may vary locally.
🟨 **B** (Thinner)	Thin Calcarenite is likely to be/may be present. JUB legs likely to pass through.
🟪 **C** (Marginal)	JUB legs may rest on Calcarenite. The Calcarenite may not necessarily be strong enough to support the JUB; punch-through is therefore more likely in Group C domains than in Group A or B domains.



	$<t_1$	t_1 to t_2	$>t_2$
$<FoS_a$	B	C	C
FoS_a to FoS_b	C	C	A
$>FoS_b$	C	A	A

Figure 4. Assessment group definitions and matrix

6 USE AND IMPROVEMENT OF THE ASSESSMENT

6.1 RESULTS PRESENTATION

Part of the Client's original scope described the need for risk maps of the site. Having developed the assessment tool detailed previously, the use of interactive flow charts was suggested.

The flow charts provided a framework for safe and consistent decision making by geotechnical engineers both on site and in the Client's office. They allowed engineers to enter the co-ordinates of the proposed jacking location, and to then immediately see the properties of the geological model and the results of the punch-through assessment corresponding to that location. In addition, the flow charts displayed site procedures appropriate to the group assignment (A, B or C) of the location, and hence appropriate to the assessed risk of punch-through at the location.

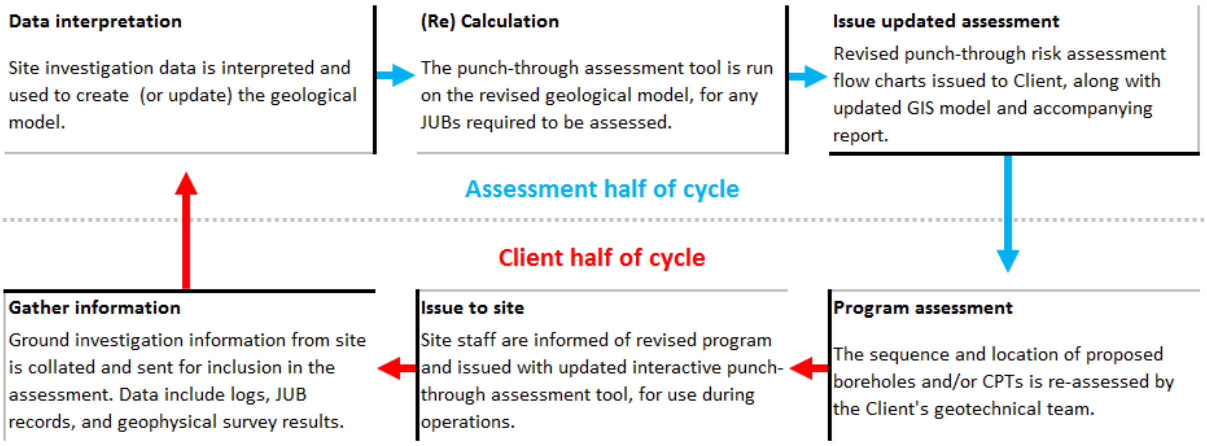
The site procedures were developed in close discussion with the Client, and were designed to impose the comparison of the near surface ground conditions encountered at each investigation point to those predicted by the punch-through assessment. In addition the procedures outlined several elevated risk indicators, the occurrence of which would trigger mandatory actions, both physical and procedural. The site procedures covered both the jacking phase and the operation phase of the work cycle.

6.2 UPDATING THE ASSESSMENT

The nature of the punch-through assessment tool and the geological model was such that it was feasible to update them as and when the Client required. Packages of new site investigation information were sent back periodically for inclusion in the model.

Upon receipt of new ground investigation information the geological model was revised to include the new data, the punch-through assessment was re-run, and the site flow charts were re-populated with the new results. The updated information was then sent back to the Client for use on site. The cycle of updating is shown in Figure 5.

Additional site investigation information influenced the geologists' interpretation of the site, which in turn affected the results of the punch-through assessment. Changes over the duration of the project are shown in Figure 6, which shows the first and last iterations of the model.



Data interpretation

Site investigation data is interpreted and used to create (or update) the geological model.

(Re) Calculation

The punch-through assessment tool is run on the revised geological model, for any JUBs required to be assessed.

Issue updated assessment

Revised punch-through risk assessment flow charts issued to Client, along with updated GIS model and accompanying report.

Assessment half of cycle

Client half of cycle

Gather information

Ground investigation information from site is collated and sent for inclusion in the assessment. Data include logs, JUB records, and geophysical survey results.

Issue to site

Site staff are informed of revised program and issued with updated interactive punch-through assessment tool, for use during operations.

Program assessment

The sequence and location of proposed boreholes and/or CPTs is re-assessed by the Client's geotechnical team.

Figure 5. (Above) The assessment updating cycle

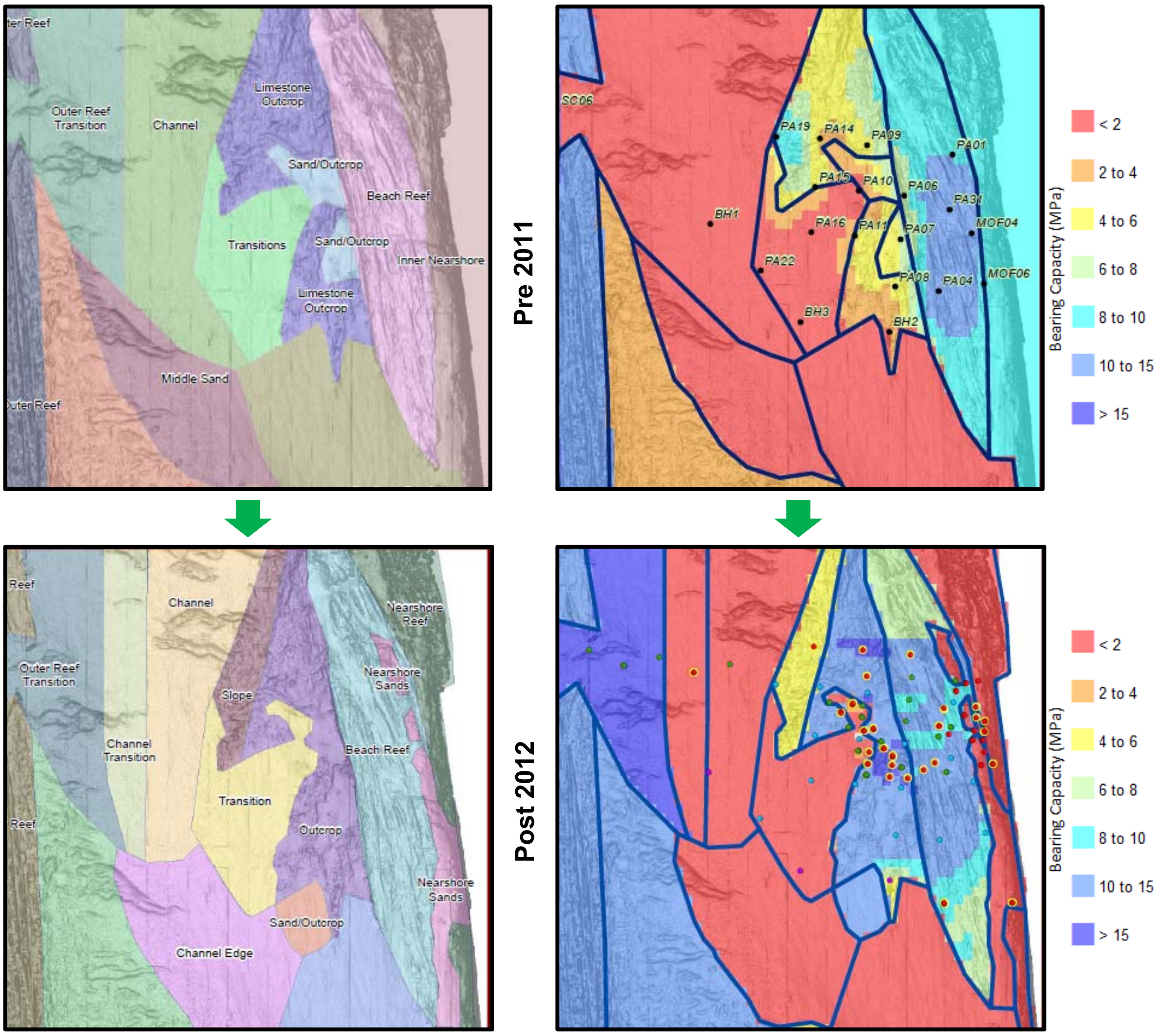


Figure 6. Geological domains (left) and example contours of allowable bearing capacity (right) before 2011 campaign (top) and after 2012 campaign (bottom). Note evolution of domain boundaries and calculated bearing capacity values.

7 CONCLUSIONS

The Assessment of Punch-through Potential provided a method by which the risk of punch-through could be assessed based on the interpretation of the available information at any given location within the site boundaries. The assessed confidence in the information was an important indicator, and influenced the assignment of risk.

The available information varied from just geophysical data in some areas of the site, to geophysical data plus several borehole and CPT investigation points in other areas. The assessment methodology was designed to make use of varying levels of information across the site.
The method of delivery of the results of the assessment was designed to provide engineers in the office and on JUBs with as much information as possible, to allow them to make informed decisions within the pre-determined framework of procedures.

The system embedded the geological interpretation, with its spatial variance, into a dynamic risk reduction application that was applied with rigour, following safety procedures.

The Assessment of Punch-through Potential significantly improved on the traditional methods of assessing punch-through risk, namely reviewing on a case by case basis, or estimating assuming a single design profile. The assessment made the work safer, its primary aim, but also improved the efficiency of the investigations by influencing the sequencing of the works.

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