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PAPER TITLE: UNDERSTANDING DAMAGE TO PIPELINES DUE TO HORIZONTAL DIRECTIONAL DRILLING
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ABSTRACT
Indiscriminate underground horizontal directional drilling (HDD) equipment presents a significant risk to buried pipelines. The risk is not well understood since there currently exists no methodology for estimating the nature and extent of pipe damage caused by such equipment. The research presented in this paper seeks to develop a greater understanding of the nature of the damage caused to pipelines by HDD equipment. The research also aims to develop a damage assessment methodology to define the extent of the damage risk. This is done by conducting a detailed examination of the physical interaction between the drilling equipment and the pipeline.

A specially designed experimental rig that incorporates a full-size HDD machine has been designed and developed and is used for this purpose. A series of experiments encompassing a range of key parameters including different sizes of test pipe, grades of steel, types of coating types of drill bits, and different degrees of lateral restraint due to soil conditions are described. This research also describes how analytical methods and Finite Element Modelling (FEM) are used to define estimated in-situ soil conditions and how this has been correlated with the lateral restraint simulated in the test rig.

The loads acting and damage inflicted on the test pipes are measured using strain gauges strategically placed on the equipment, and the related pipe damage is quantified using a laser scanning technique. The observed damage is correlated with appropriate HDD parameters. It is found that the concept of ´ploughing force´ helps to reduce the number of independent HDD parameters that contribute to the damage. A generalized quantitative relationship between HDD rigs, bit types, soil conditions and the resultant damage is proposed.

1. INTRODUCTION

External interference (EI) is the major cause of failures in the pipeline industry, with international data indicating that almost 50% of pipeline failures are due to EI events. Drilling equipment, which includes Horizontal Directional Drilling (HDD) equipment, presents a particularly significant threat to buried pipelines. For instance, EI data presented in [1] has shown that while excavator incidents represent 54% of all pipeline damage incidents, only 4% of these incidents resulted in loss of containment events. Conversely, while drilling operations represented only 4% of damage incidents, nearly 50% of these drilling incidents resulted in loss of containment. This demonstrates the significant threat that drilling operations present to pipelines. In addition, in recent years the use of HDD equipment to install utilities has increased, especially in built-up areas, and is expected to continue to increase, subsequently increasing the risks to pipelines and society [2].

Drilling equipment damage to pipelines is poorly understood because there have been no detailed studies of the interaction between drilling equipment and buried pipelines. Subsequently, there is no basis for estimating the type and severity of damage (including superficial damage, gouging, denting or penetration) due to types of drilling equipment.

The present research has aimed to address this gap in the current knowledge. A full-scale fit-to-purpose experimental rig was designed, fabricated and housed in the University of Wollongong EIS R&D Facility at Russell Vale, New South Wales, Australia. A number of experiments were carried out on this test rig. The experiments allowed live, direct visual observation of the interaction between HDD equipment and pipelines.

The research has focused on the following outcomes:

- A qualitative understanding of the nature of damage caused by HDD equipment;
- An understanding of the relationship between various parameters to those that have the greatest influence on pipe damage during the interaction;
- The development of a predictive model to quantify pipe damage due to HDD impact;
- The development of a detailed understanding of generic gouging mechanisms due to externally applied forces.

This paper presents a description of the experimental rig, the experiments carried out, characteristic features of the observed damage and correlations of the damage with the HDD parameters associated with the first two outcomes listed above. Research activities associated with the latter two outcomes is still ongoing at time of preparation of this paper.

2. MOTIVATION AND BACKGROUND

AS2885.1 [3] adopts a unique approach towards pipeline wall thickness design, compared to other pipeline design codes. Traditional design codes adopt an all-encompassing Design Factor based on Location Class. Historically, has been presumed to provide adequate protection against EI threats. By contrast, AS2885.1 requires the explicit consideration of all EI threats (e.g. penetration resistance, gouge length with respect to critical defect length, etc.) in the wall thickness definition. The AS2885.1 approach is demonstrated graphically in **Figure 1**.

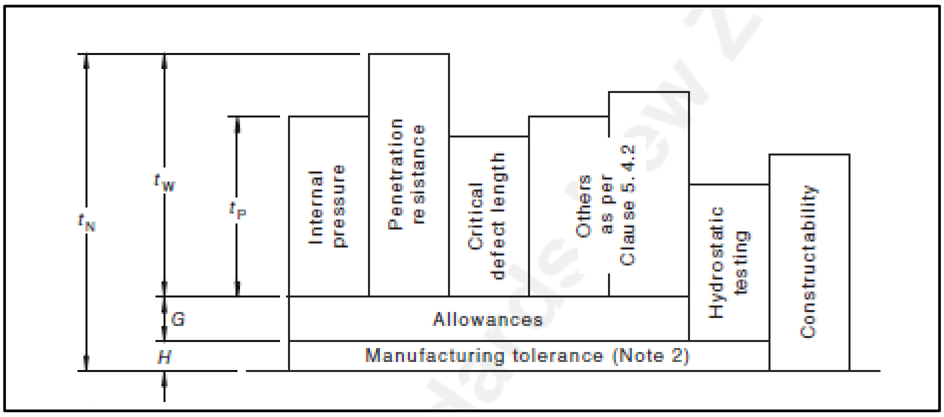


Figure 1 AS2885.1 Wall Thickness Design Approach [3]

Excavator impacts to pipelines has been the subject of extensive research under APGA RSC sponsorship [4]. The outcomes of that specific research have been incorporated into AS2885.1, providing a methodology for assessing resistance to penetration due to excavator impacts and defines the design requirements to ensure that adequate wall thickness is implemented to satisfy AS2885 requirements.

However, there is no such methodology for the assessment of damage to pipelines due to drilling equipment. There are anecdotal accounts resulting from both informal experiments and accidental damage incidents, but such data has no predictive value. Hence assessments for drilling damage (if performed at all) are based only on this anecdotal evidence, with little, if any, substantive basis. These assessments tend to be applied in an inconsistent manner dependent on the opinions of the individuals involved in the assessment. Hence the assessment tends to be little more than an "educated guess."

Therefore, it is necessary to achieve an appropriate level of knowledge regarding the damage to pipelines due to HDD equipment. The aim is to develop an assessment methodology that will allow an appropriate and consistent approach to ensure that adequate wall thickness is defined to provide to provide adequate protection against HDD impacts, ensuring that the AS2885 safety requirements are satisfied in a cost-effective manner.

3. HDD – PIPELINE INTERACTION PARAMETERS

The initial phase of this research involved a review of how to explore HDD - pipe interaction [5]. This included the consideration of analytical or Finite Element modelling, full-scale field testing and/or laboratory testing, The review concluded that the most suitable approach would be to conduct laboratory testing since this would permit a thorough review of various parameters to understand their influence during the HDD equipment-pipe interaction as well as providing the opportunity to visualise the interaction. To achieve these ends, a realistic laboratory testing rig with the capability to evaluate various parameters was proposed and developed.

Also, as part of this initial phase, a list of key parameters was developed, defining those which were considered relevant when defining the nature and extent of pipe damage due to HDD impact, which would be needed to be included in the test program. These included:

- HDD drill rod thrust (F) and torque (τ)
- HDD drill rod axial speed (v) and rotational speed (ω);
- Pipe outer diameter (D);
- Pipe wall thickness (t);
- Impact offset position (d);
- Soil resistance, lateral and axial (F_{soil});
- Drill bit type;
- Duration of contact.

These parameters are shown schematically in **Figure 2** and are briefly discussed in the following sections.

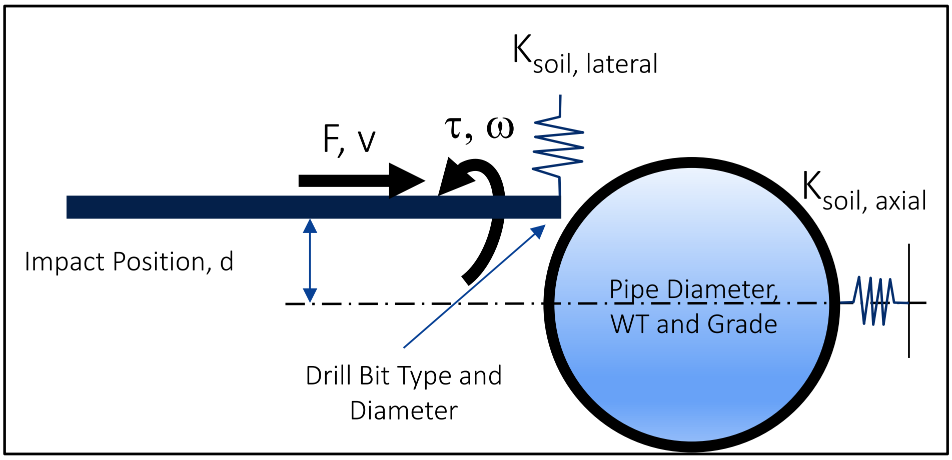


Figure 2: HDD-Pipeline Interaction Parameters

3.1 HDD Drill Rod Thrust and Torque

Understanding the HDD thrust (F) and torque (τ) during the interaction was considered paramount since these represent the loads imposed on the pipe. HDD equipment rated thrust and torque represent the upper limits of the possible loads imposed on the pipeline. However, it was considered likely that the actual thrust and torque would be limited by other constraints. Therefore the relationship between these forces and other parameters would need to be investigated and understood from the test program.

3.2 Soil Resistance

3.2.1 Lateral Soil Resistance

The lateral soil resistance was considered to be a key parameter in the interaction, particularly regarding the forces imposed on the pipeline. Anecdotal evidence suggested that a low lateral soil resistance would cause the HDD drill bit to divert (slip) off the pipe, causing relatively little pipe damage, while high lateral soil resistance would increase the impact forces imposed on the pipe and also the increase the duration of the interaction. Therefore, a range of lateral soil resistances relevant to local conditions would need to be investigated in the test program to understand the influence of lateral restraint on the impact loads (i.e. torque, thrust).

3.2.2 Axial Soil Resistance

Axial soil resistance is the restraint provided by the soil on the pipe in the drilling direction. Compared to the possible lateral movement, the movement parallel to the drill axis has been assumed to be negligible. This amounted to assuming that the axial soil resistance was infinitely large in the test program.

3.2. Drill Bit Types

A number of drill bit types have been used in the HDD operation since drill bit types were considered to have a considerable influence on the nature and extent of the damage caused to the pipe. Hence a number of drill bit types, including varying bit sizes, representing what are considered to be the most credible for use in Australia have been included in the test program [6].

3.3 Impact Position

The impact position (offset d) was considered to possibly influence the nature and extent of damage to the pipe. As shown in Figure 2, the impact location could vary from zero to a maximum of D/2. Therefore, a number of values of 'd' were needed to be evaluated in the program to ensure the most critical conditions were captured in the results.

3.4 HDD Drill Rod Axial and Rotational Speeds

The axial and rotational speeds of the HDD bit were considered necessary variables in the test program to assess their influence on the nature and extent of damage. Low axial speed/high rotational speeds would result in more "gouging" contacts per interaction, compared to the high axial speed/low angular speed case. The resultant interaction needed to be understood to ensure that the most critical condition was captured from the test results. Also, high axial speeds/low rotational speeds may tend to result in a higher tendency for "puncture" impacts on the pipe wall, especially for 'head-on' contact (d = 0), rather than gouging. Therefore a realistic range of axial/rotational speeds needed to be addressed in the test program.

3.5 Pipe Diameter

Pipe diameter, or more specifically, pipe diameter relative to HDD drill bit width, may have an influence on the extent of damage. This has therefore been addressed in the test program. A range of pipe diameters and HDD drill bit widths have been used in the tests to assess the influence.

3.6 Pipe Wall Thickness and Material Grade

Pipe wall thickness may influence the nature of the damage, particularly if denting is a resultant failure mode. A range of pipe wall thicknesses have been included in the test program.

Similarly for material grade, an understanding of the influence of material grade on the nature and extent of damage (e.g. gouge depth) was considered necessary to obtain from the test program.

3.7 Duration of Contact

The duration of contact is the time for which the HDD drill bit will engage with the pipe prior to an attentive operator ceasing the drilling operation. This parameter was believed to be particularly relevant for the specific scenarios where the drill tip is "locked" into one location on the pipe and not for instances where the drill bit diverts to the side of the pipeline. Duration of contact has been monitored in the test program.

3.8 Test Parameters

The experimental HDD rig was subsequently designed to allow for the variation of the variables as listed in Table 1. Table 1 also shows the parameters which needed to be measured and recorded during the HDD equipment-pipe interaction.

Variable Parameters	Drill bit type and size
	Pipe OD, WT and Grade
	Soil lateral restraint
	Impact position
	HDD rod axial/rotational speed
Measured/Recorded Parameters	HDD rod torque and thrust
	Forces acting on pipe
	Soil lateral restraint and movement
	Contact duration
	Gouge depth and length
	Dent depth

Table 1 Test Parameters

4. HDD TEST EQUIPMENT DECRIPTION

4.1 Experimental Test Rig Requirements

The functional requirements for the HDD test rig were set out as follows:

- It should enable experiments to be carried out on test pipe sections of a range of diameters from DN150 to DN500;
- The interaction between the drill bit and the pipeline should be open to view, so that it could be observed and video recorded;
- It should be possible to simulate the effect of the soil lateral restraint on the drill bit as it interacts with the pipe;
- It should be possible to conduct multiple experiments with the same configuration in order to ascertain repeatability of the experimental results;
- The test parameters identified in Table 1 should be controllable and measurable.

4.2 Experimental Test Rig and accessories

Figure 3 shows an overall schematic diagram of the experimental rig.

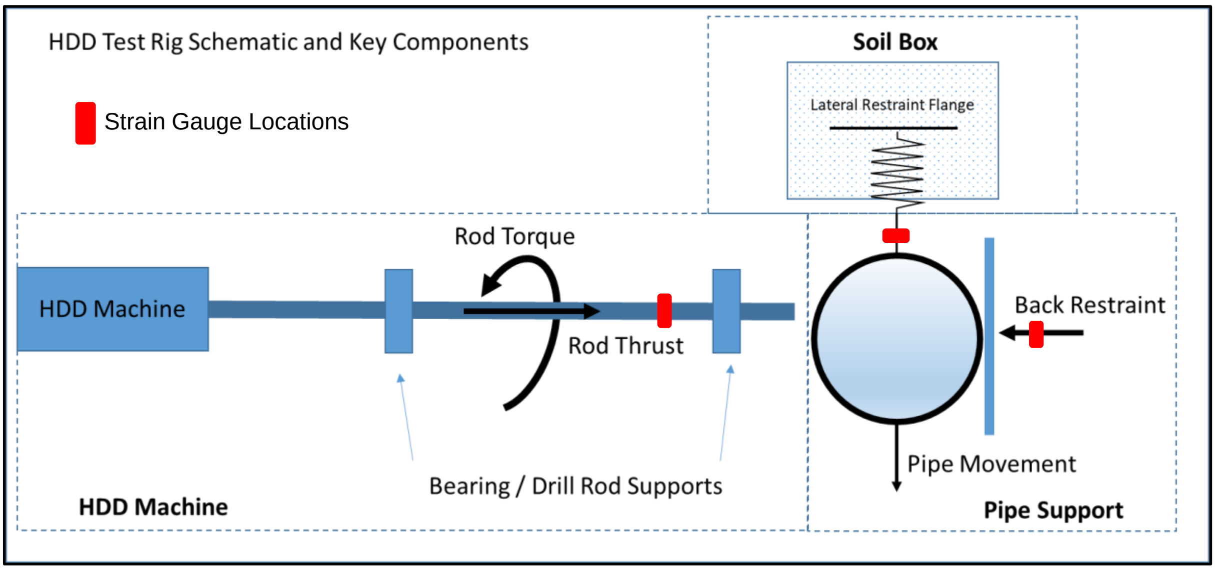


Figure 3: HDD Experimental Test Rig Schematic

Also shown in Figure 3, the strain gauges were attached to the drill rod to measure the drill rod thrust and torque as well as on the soil rod and pipe cradle support.

The main components of the experimental rig are:

- HDD Machine Assembly
- Pipe Support with pendulum and cradle
- Soil box including lateral restraint flange and rod

An overall view of the test rig is shown in Figure 4.

Figure 4: HDD Test Rig

Key features of each component are described in the following paragraphs.

4.3 HDD Machine Assembly

The HDD machine assembly provides the torque and thrust for the impact testing. The HDD machine is a full-size HDD rig, namely a Construction Manufacturing Services (CMS) 3020, which has the rated capacities of 5,000 Nm torque and 150 kN thrust. The rig allows for variable rotation speeds (up to approx. 60 rpm) and axial travel speeds (minimum is approx. 5 mm/sec).

An earlier phase of the project (Phase 1) made use of a hydraulic rock drill, but this has a limited capacity of only 500Nm of torque. However, regardless of this limitation, these results have also been included in the overall analysis.

4.4 Pipe Support

The pipe support consists of a main frame supporting a pendulum-and-cradle assembly suspended from the frame cross-bar. The pendulum fulcrum can be shifted sideways for alignment. The pendulum rod is about 2m long, which rotates to replicate the relative motion between the HDD drill rod and the pipe. The length of the pendulum rod minimises any error due to the rotational shift compared to lateral shift. The cradle on the pendulum base has a square base measuring about 620 mm × 620 mm, on which 500 mm long test pipes of different diameters can be mounted and fixed in place using C-clamps of compatible sizes.

The back of the cradle is fitted with four short support rods that rest against the vertical plate at the bottom of the rig frame. The thrust force on the test pipe can be measured by strain gauges attached to these four support rods that function as load cells.

4.5 Soil Box and Soil Rod

A particular feature of the test rig is the soil lateral restraint modelling. During an actual drilling operation, the HDD drill rod flexes 'around' the pipe due to the action of a concentrated contact force occurring between the pipe and the drill bit tip. Movement away from the pipeline is resisted by the following:

- a distributed resistance along the length of the HDD string due to soil restraint, K_{ground}
- the bending stiffness resistance of the drill string.

In the experiments, the *relative* movement between the HDD drill rod and the pipe is achieved by allowing sideways movement of the test pipe. The lateral soil restraint is modelled by an equivalent single spring with stiffness K_{eq} applied to the test pipe. Restraint modelling has been carried out to convert the actual in-situ ground restraint condition, K_{ground} to an equivalent single end point restraint, K_{eq}, as shown below in Figure 5.

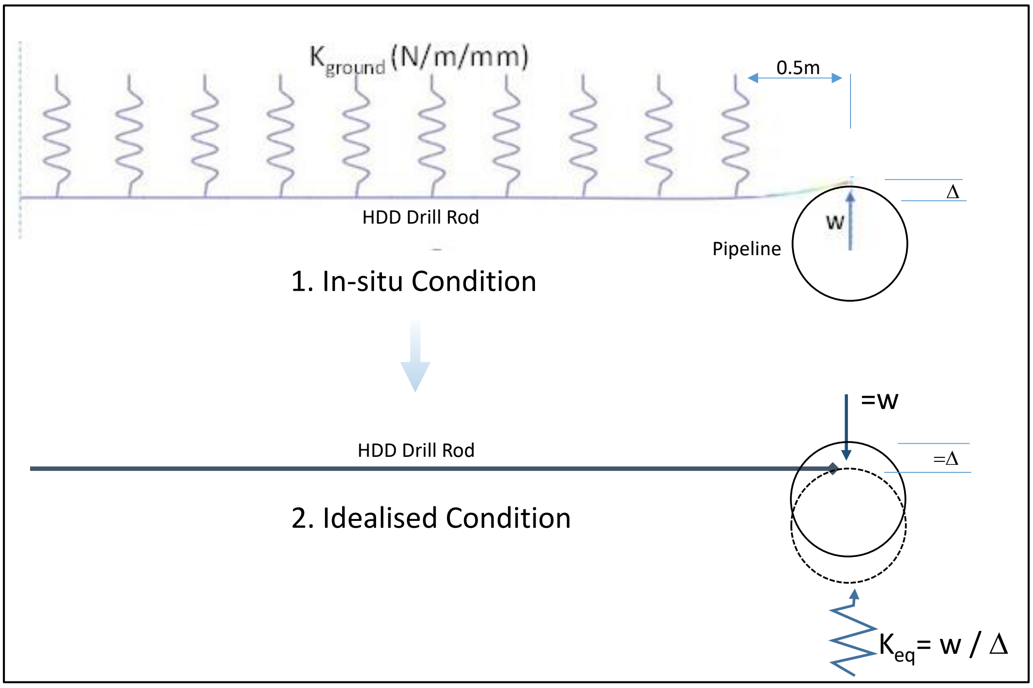


Figure 5: Modelling of lateral restraint

A large open-top steel box, located adjacent to the pipe support frame was filled with soil. A 'soil rod' connects the pipe cradle to a removable flange that is completely embedded in the soil during the experiment. The resistance provided by the soil is proportional to the size (diameter) of the flange - the larger the flange diameter, the larger the soil resistance. This technique simplifies the experiments by allowing a physical simulation of soils with different degrees of stiffness by varying the flange size (Figure 6).

An equivalent stiffness was defined in the experimental results from the lateral force measured within the soil rod (W) and the pipe movement (Δ) during the HDD interaction. The equivalent stiffness determined in the test results could then be used to relate the test conditions to actual ground conditions.

Figure 6 Soil Box, Soil Rod and Accessories

4.6 Data acquisition

During the experiment, the relevant HDD parameters are measured in terms of the strains generated in the drill rod, cradle support rods and soil rod. The strains measured by the strain gauges fixed on the cradle support rods are recorded separately from the strain gauge readings on the rotating drill rod. The latter measurements are conveyed via a wireless transmitter and receiver to the data acquisition software installed on a computer (Figure 7).

The data acquired from the strain gauges was subsequently converted to forces/torque and correlated, as shown below in Figure 8. This allowed the correlation of the different loads during the HDD – pipe interaction.

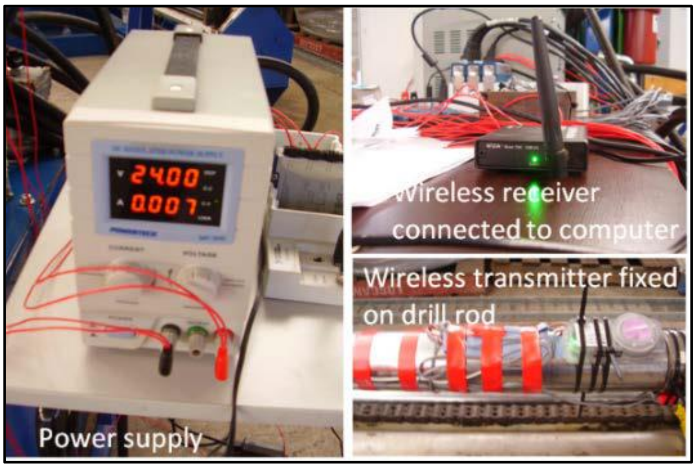


Figure 7 Data acquisition equipment

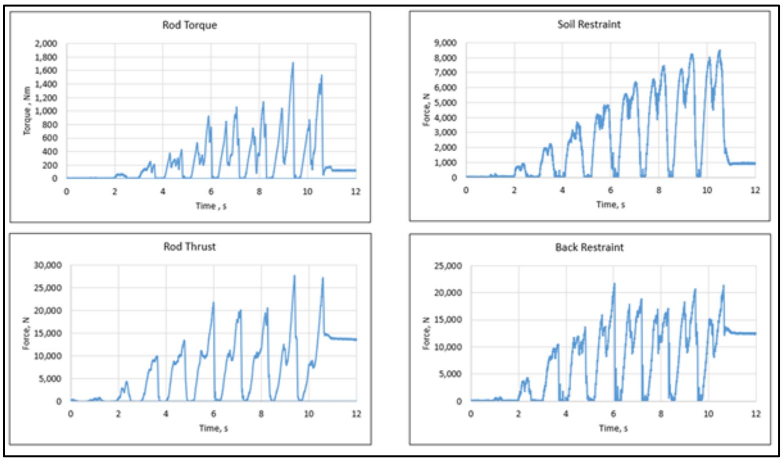


Figure 8: Load history data during a typical interaction

4.7 Pipe Damage Measurement

Pipe damage has been measured using the commercially available 'HandyScan 3D' laser scanner and the accompanying 'VXElements' software. A representative example of pipe damage and the corresponding scanned image is shown in Figure 9. The damage was defined in terms of the overall damage area (length and width), maximum depth of gouge, maximum length of gouge and, if applicable, depth of dent.

Figure 9: Example of Pipe damage and scanned image

4.8 Test Procedure

Each experiment was carried out in the following sequence of steps:

1. Installing the test pipe on the cradle;
2. Clamping of the test pipe in place;
3. Setting the impact offset (lateral distance between the horizontal axis of the drill rod and the vertical axis of the pendulum rod/pipe specimen) using the lock screws on either side of the fulcrum;
4. Installing the desired drill bit on the drill rod;
5. Removing some soil from the soil box to gain access to the buried flange;
6. Installing the flange of the desired size on the soil rod to simulate the desired degree of soil stiffness;
7. Re-filling the soil and compacting it in the soil box around the flange, to remove any cavity created during the previous experiment;
8. Adjusting the position of the forward drill rod support using the drill rod support control lever to minimize the drill rod cantilever;
9. Calibrating the data acquisition system;
10. Starting the data acquisition;
11. Starting drill rod rotation using the drill rod rotation control lever on the HDD machine;
12. Starting drill rod feed (advance towards test pipe) using the feed control lever on the HDD machine, until impact;
13. Continuing the drill bit-test pipe interaction until the test pipe is displaced laterally to the maximum extent possible;
14. Stopping data acquisition;
15. Withdrawing the drill pipe back to the starting position;
16. Restoring the cradle to the position (vertical pendulum rod with the desired offset distance) for the next test.
17. Each test was conducted three times on each pipe sample by rotating the pipe by 120^o

5. EXPERIMENTAL RESULTS

5.1 Tests Completed

A total of 140 tests have been completed to date (including Phase 1) , encompassing 52 different test parameter scenarios. The range of parameters tested are defined in the following sections.

5.1.1 Pipe Parameters

The following pipe sizes, coatings and steel grades were used in the test program:

- Outer diameter 168mm, wall thickness 5.5mm with 2.5mm external tri-laminate coating, steel grade X42
- Outer diameter 273mm, wall thickness 4.8 with 2.5mm external tri-laminate coating, steel grade X65
- Outer diameter 273mm, wall thickness 6.4 with 1mm external Naprock coating, steel grade X65
- Outer diameter 508 mm, wall thickness 9.5 mm with ~0.5 mm FBE external coating, steel grade X52
- Outer diameter 508 mm, wall thickness 12.2 mm with ~0.5 mm FBE external coating, steel grade X70

5.1.2 HDD Bit Types

The HDD bit types included in the test program, representing those commonly used in Australia are shown below in Figure 10.

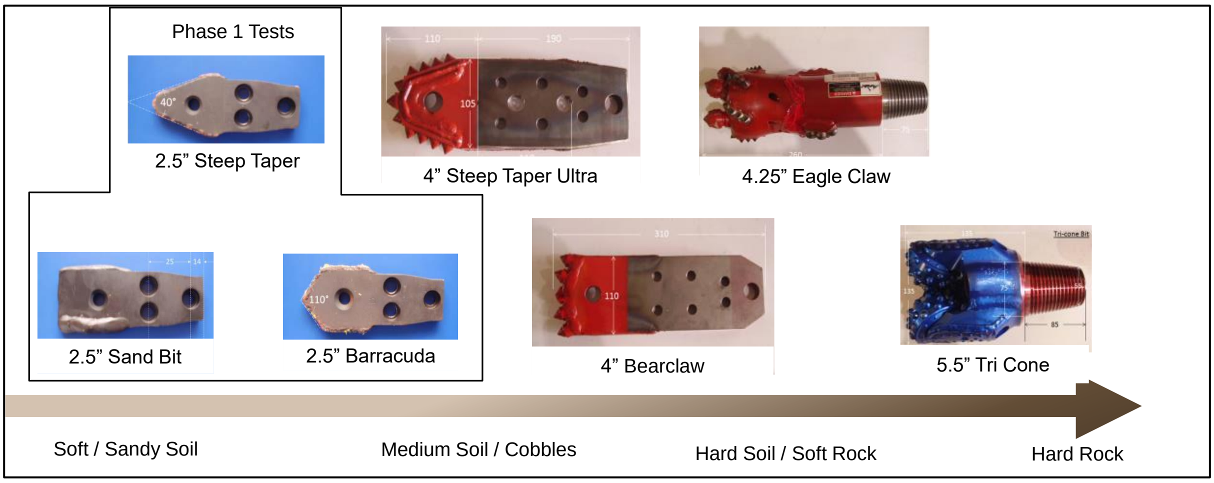


Figure 10: Test HDD Bit Types

5.1.3 Other Test Parameters

The range of other test parameters included in the test program are summarised below in Table 2.

Parameter	Test Range
Impact position offset	0-150mm
Rotational speed	60 - 180rpm
Axial speed	5 mm/sec
Contact duration	Variable
Soil restraint flange diameter	200 mm – 600 mm

Table 2 Experimental Parameters

5.2 Test Results

The test results obtained to date have provided an understanding of the nature of the damage caused by various HDD bits as well as providing insight into the relationship between the various parameters discussed in Section 3. In addition, some understanding has been gained regarding the parameters influencing the resultant damage. However, at the time of writing, this work is still ongoing, as is the development of a predictive model for HDD – pipe impacts and the detail analysis into the mechanism of gouge creation.

The results shown in the following sections address the following:

- Observed damage (qualitative description)
- Force relationships and influence of key parameters
- Damage relationships and influence of key parameters

5.3 Observed Damage

The observed damage provides a qualitative description of the nature of the damage caused by HDD impact. The following figures show the damage for a selection of bit types.

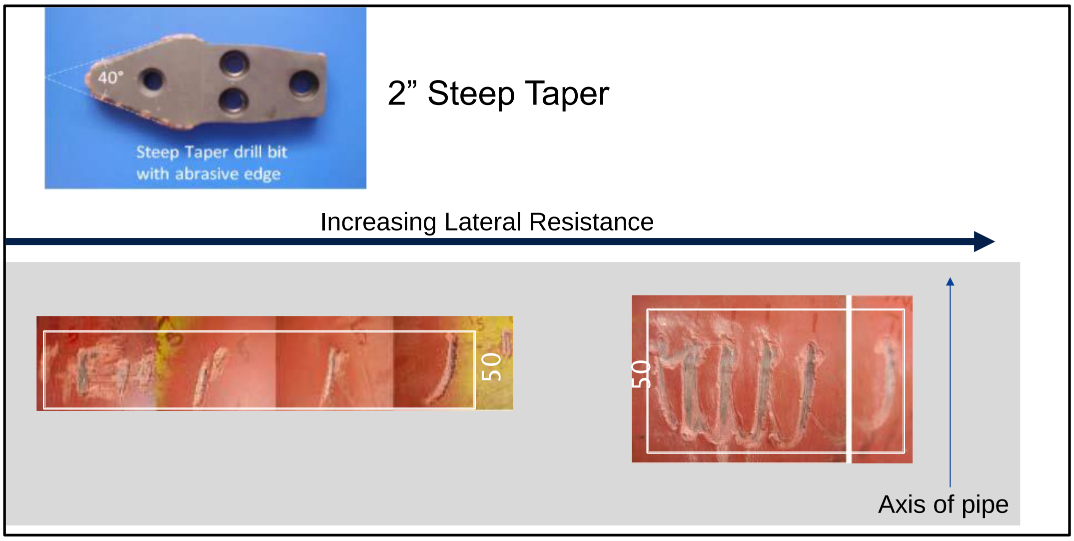


Figure 11: Observed Damage 2" Steep Taper Bit

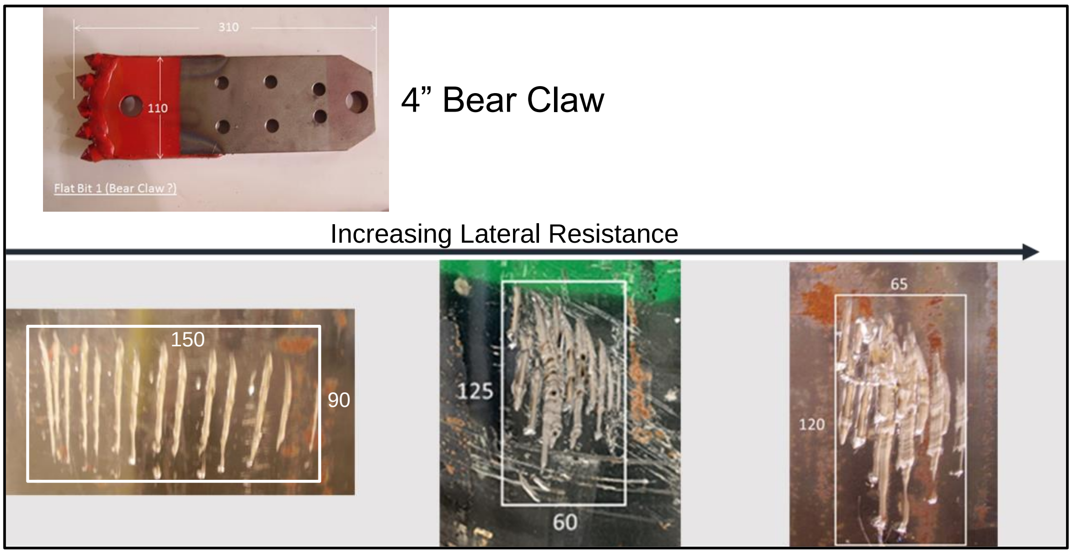


Figure 12: Pipe Damage 4" Bear Claw

The observed damage from the blade bits including the taper, bear claw and eagle claw all consisted of a series of gouges, aligned with the pipe axis (i.e. perpendicular to the HDD drill rod axis) and spaced across the pipe circumference. The spacing between the gouges decreased with increasing lateral resistance, becoming almost coincident at higher lateral restraints. The length of the gouges was related to the diameter described by the HDD bit.

The damage resulting from the tri-cone bit type was significantly different, as shown in Figure 13.

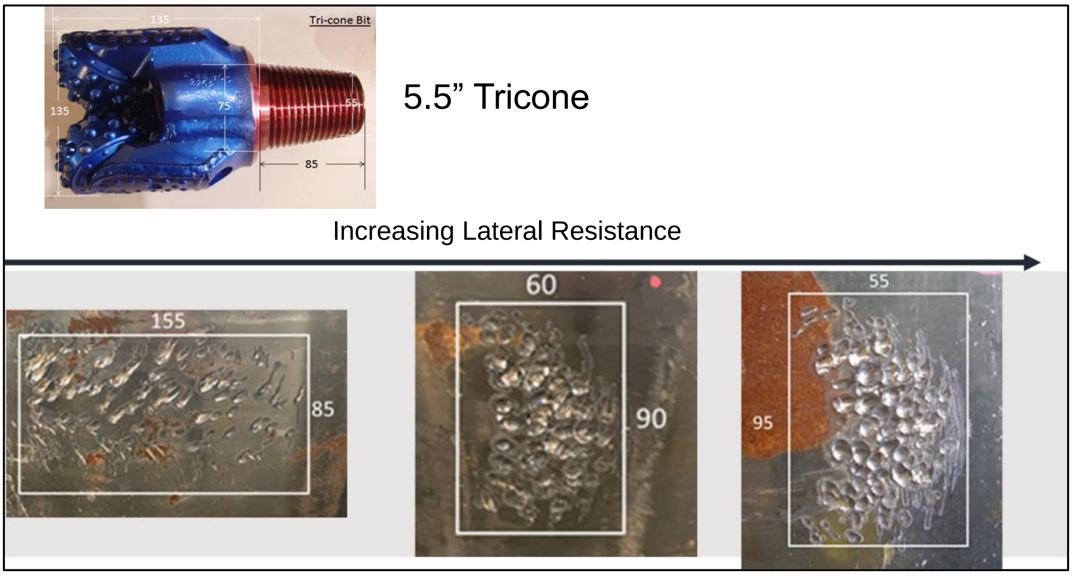


Figure 13: Pipe Damage 5.5" Tri-cone

The resulting damage was a series of dimples, becoming more congested as the lateral restraint increased. The depth of the dimples did not vary significantly with increasing lateral restraint.

5.4 Force Relationships

The load relationships presented in the following sections include the following:

- Relationship between HDD rod torque and thrust
- Influence of lateral soil restraint on resultant HDD rod torque
- Influence of bit type
- Influence of rotational speed

5.5 Torque and Thrust Relationship

The relationship between the HDD rod and torque during the impact interaction is shown below in Figure 14.

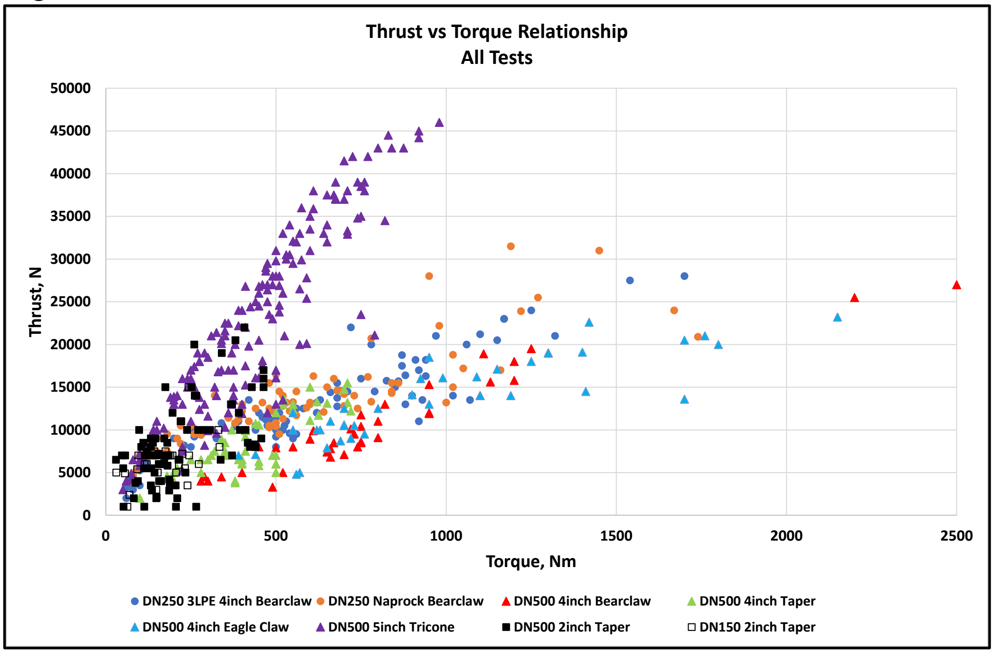


Figure 14 Thrust vs Torque relationship

These results demonstrates that there is high correlation between the thrust and the torque for all bit types. The tri-cone is seen to have a much higher thrust component compared to the other bit types, which is consistent with the nature of the nature of interaction between the tri-cone and the test pipe.

5.5.1 Influence of Lateral Soil Restraint

The influence of the soil lateral restraint on the resultant HDD rod torque for all tests is shown below in Figure 15.

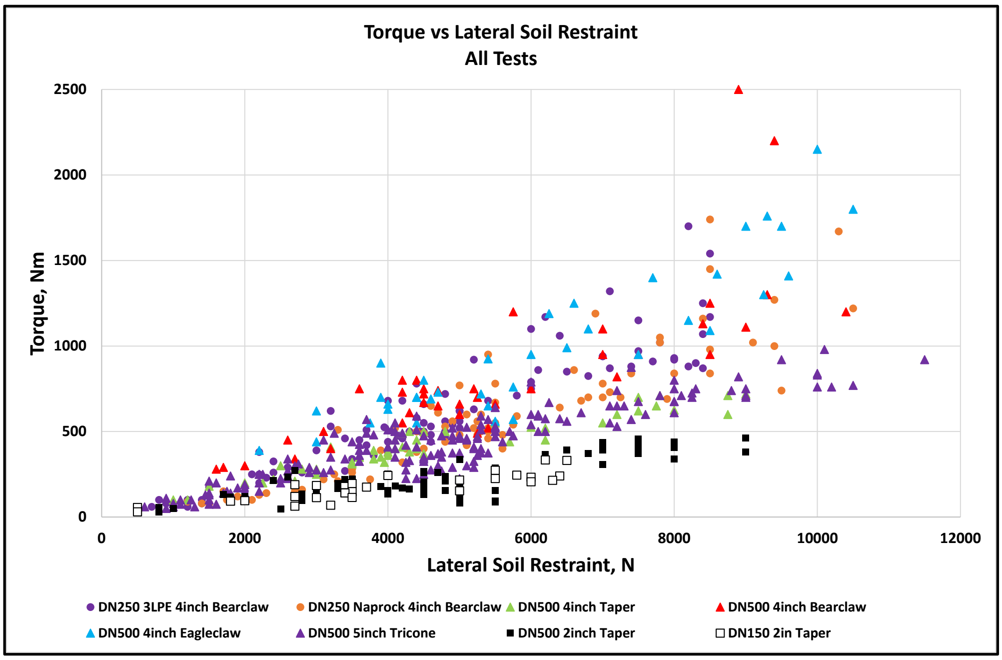
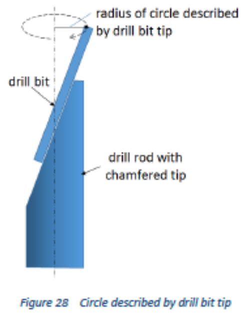


Figure 15: Torque vs Lateral Soil Restraint

The following observations can be made regarding the above results:

- There is a strong correlation between the lateral soil restraint and the resultant torque in the HDD rod for all test scenarios. This confirms that higher soil restraint will result in higher impact loads on the pipeline.
- The resultant torque appears to be dependent on other factors including bit type and diameter. The influence of bit diameter can be eliminated using a "plough force" term as an alternative to torque, as discussed below.
- The torque does not appear to be influenced by pipe diameter.

The 'plough force' term, as shown below in Figure 16 has been used to normalise different HDD tip diameters.



$$Ploughing\ force\ (N) = \frac{Drill\ torque\ (Nm)}{Radius\ of\ the\ circle\ described\ by\ drill\ bit\ tip\ (m)}$$

Figure 16: Plough Force

The relationship between the lateral soil restraint force and the resultant plough force is shown below in Figure 17.

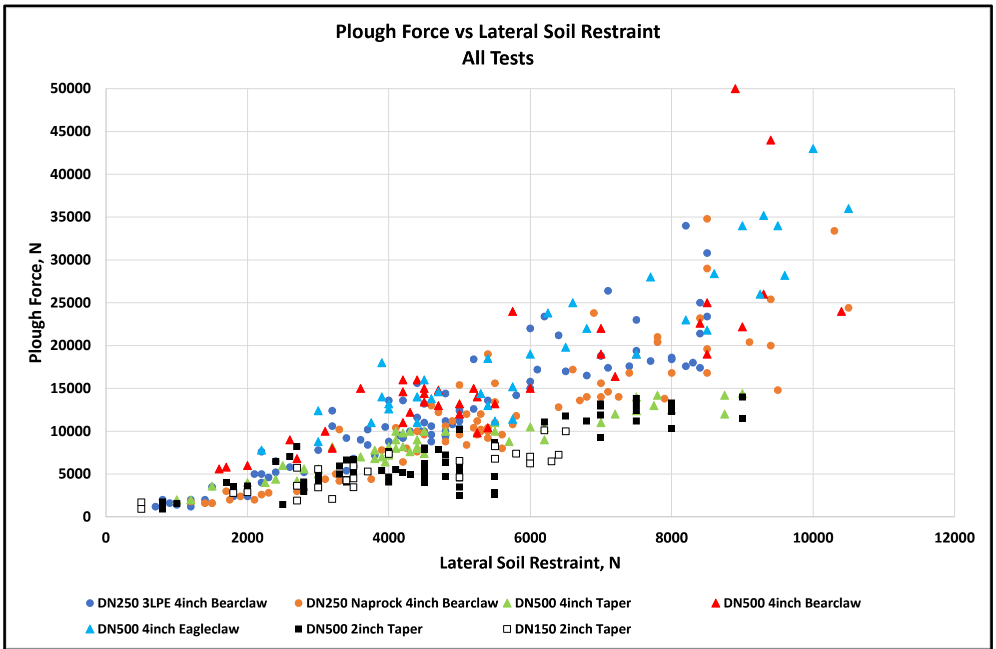


Figure 17 Plough Force vs Lateral Soil Restraint

These results show that the Plough Force imposed on the pipe is consistent for the similar bit types over a range of bit diameters. Therefore, the use of Plough Force concept can reduce the number of independent variables that contribute to pipe damage.

5.5.2 Influence of Bit Type

The influence of bit type on resultant torque is demonstrated in Figure 18 by isolating these parameters from otherwise identical test conditions.

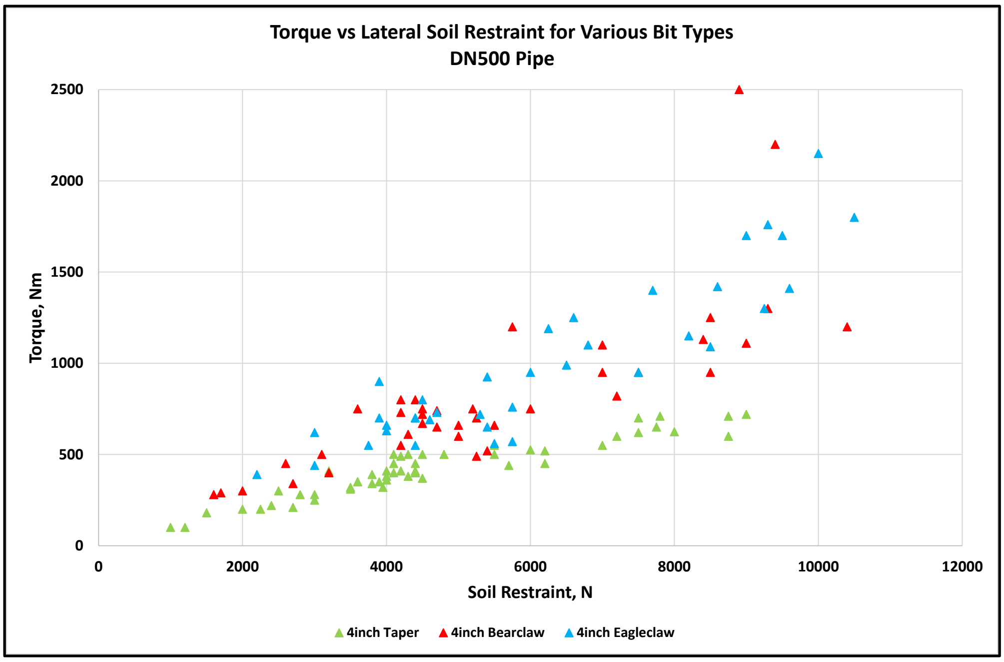


Figure 18: Influence of Bit Type on Torque

These results clearly show that the bit type has an influence on the resultant torque, with a lesser resultant torque for the tapered bit compared to the other bit types. The reason for this is still being investigated, but it is apparent that the bit type needs to be addressed in the HDD-Pipe damage assessment.

5.5.3 Influence of Rotational Speed

The influence of rotational speed on torque is shown below in Figure 19.

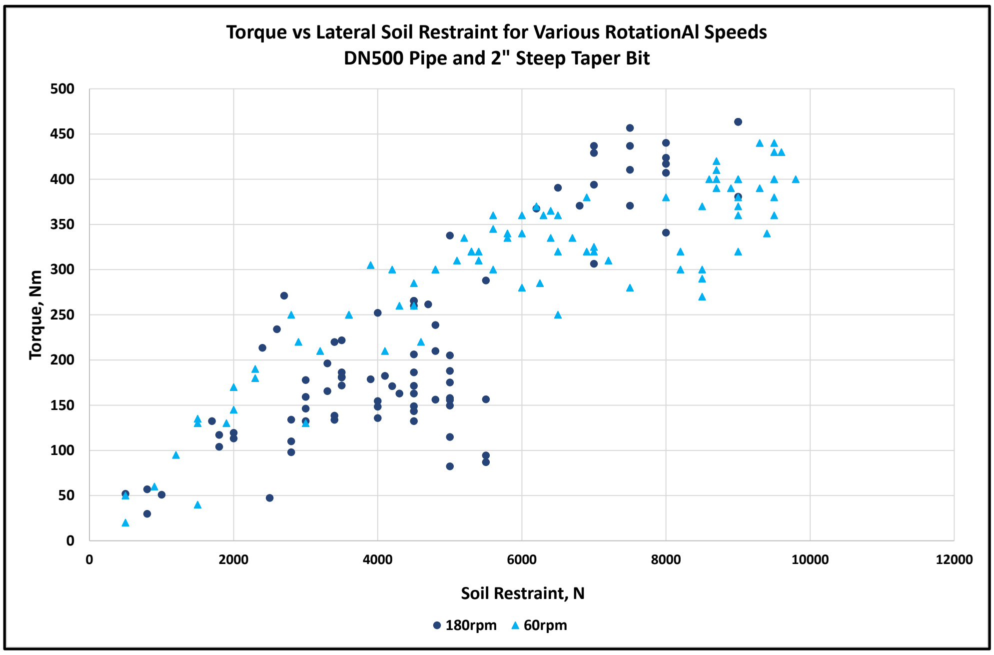


Figure 19: Influence of Rotational Speed on Torque

These results demonstrate that the rotational speed does not influence the resultant torque, hence can be ignored in the HDD-Pipe interaction analysis.

5.6 Damage Relationships

The damage relationships presented in the following sections include the following:

- Relationship between HDD rod Plough Force (Torque) and peak gouge depth;
- Relationship between HDD rod thrust and peak gouge depth;
- Influence of bit type;
- Influence of pipe diameter;
- Influence of impact position.

5.6.1 Plough Force (Torque) and Gouge Depth

The relationship between the HDD Plough Force and peak gouge depth is shown below in Figure 20.

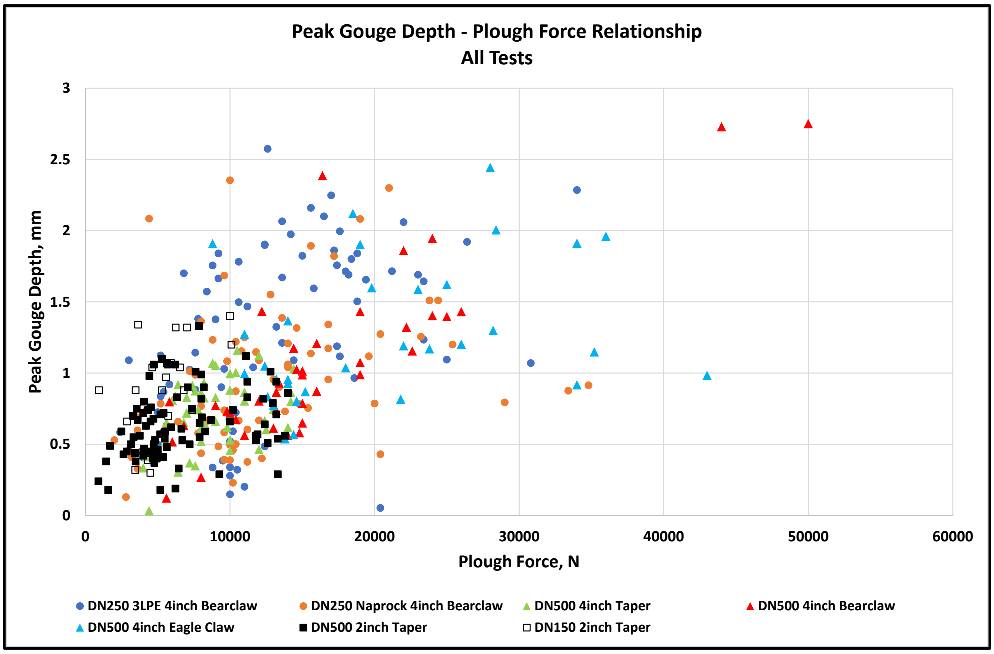


Figure 20 Peak Gouge Depth vs Plough Force

While the result show a distinct trend, relating peak gouge depth to Plough Fore, there is an apparent spread in the results. Further assessment has been carried out to reduce or further understand the cause of the spread.

The use of the plough force concept demonstrates a consistent gouge depth for plough force, independent of bit diameter.

5.6.2 Damage and Thrust

The relationship between HDD rod thrust and peak gouge depth has also been investigated, the result of which are shown below.

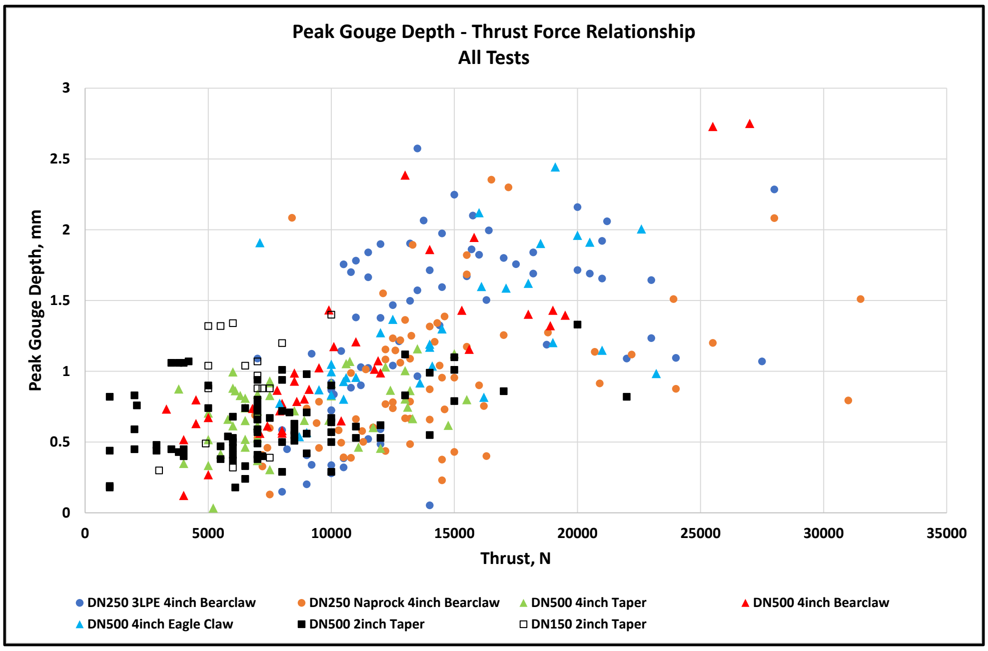


Figure 21 Peak Gouge Depth vs Rod Thrust

It is apparent from Figure 21 that the use of thrust does not improve the gouge depth prediction, hence, plough force is a more appropriate predictor of peak gouge depth.

5.6.3 Influence of Bit Type

The influence of bit type on the peak gouge depth is shown below in Figure 22.

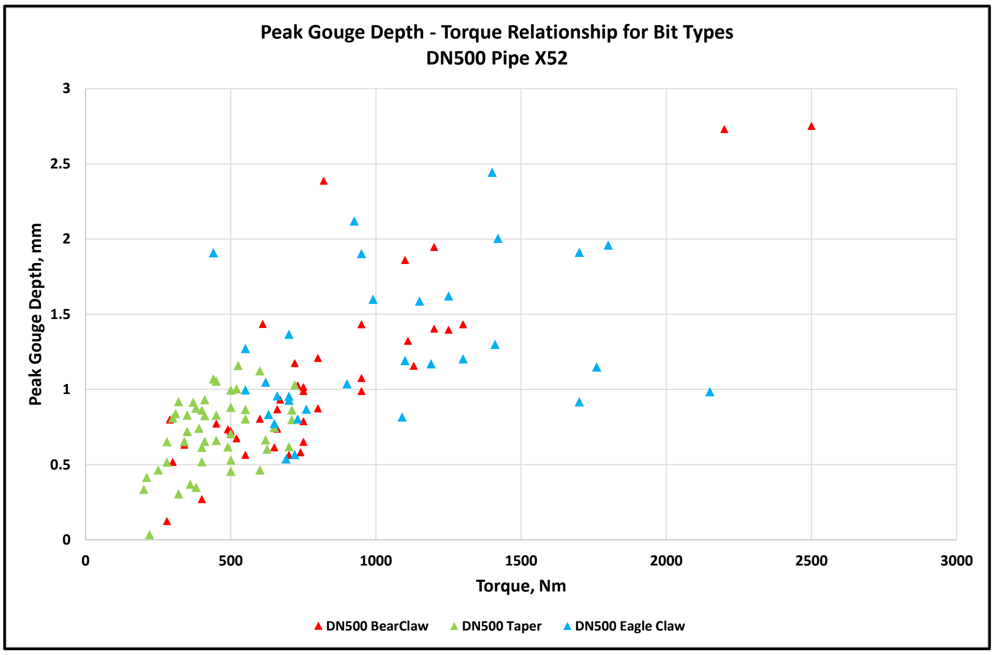


Figure 22 Influence of Bit Type

The results in Figure 22 show that the bit type appears to have an influence on the maximum torque, as discussed in Section 5.5.2, but the depth – torque relationship is consistent with other bit types.

5.6.4 Influence of Pipe Diameter

The influence of pipe diameter has been further assessed to determine if this influences the gouge depth. The results for two pipe diameters and identical bit types are shown below in Figure 23.

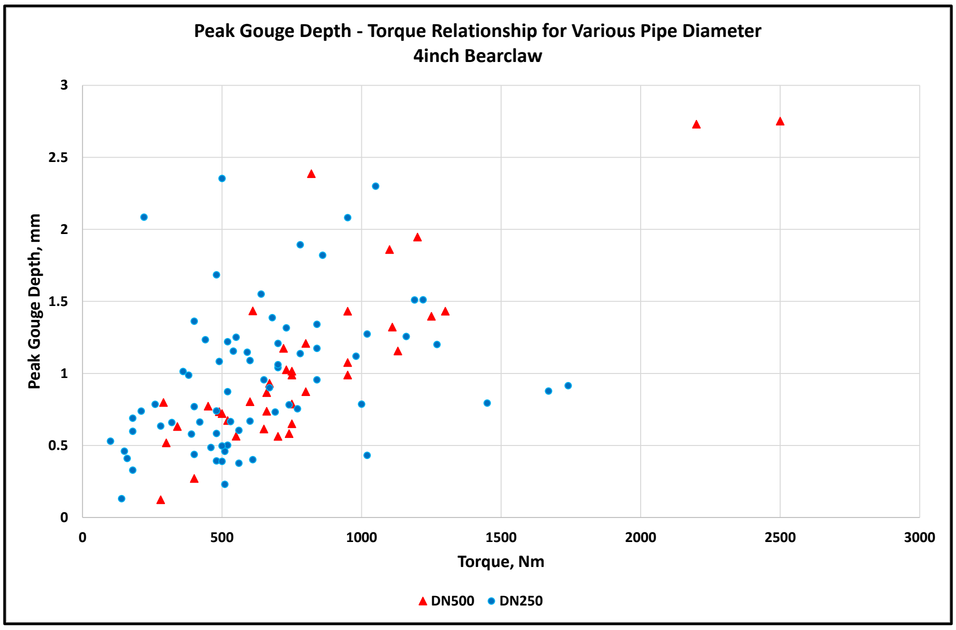


Figure 23 Peak Gouge Depth vs for two pipe diameters

The results show that smaller diameter pipe has a greater spread of gouge depths while there is a strong correlation between peak gouge depth and torque for the DN500 pipe. The reason for this is further addressed in Section 5.6.5.

5.6.5 Influence of Gouge Position

The influence of the gouge position, relative to the HDD-pipe axis (i.e. 0 deg represents 0mm offset, d in Figure 2) is shown below in Figure 24.

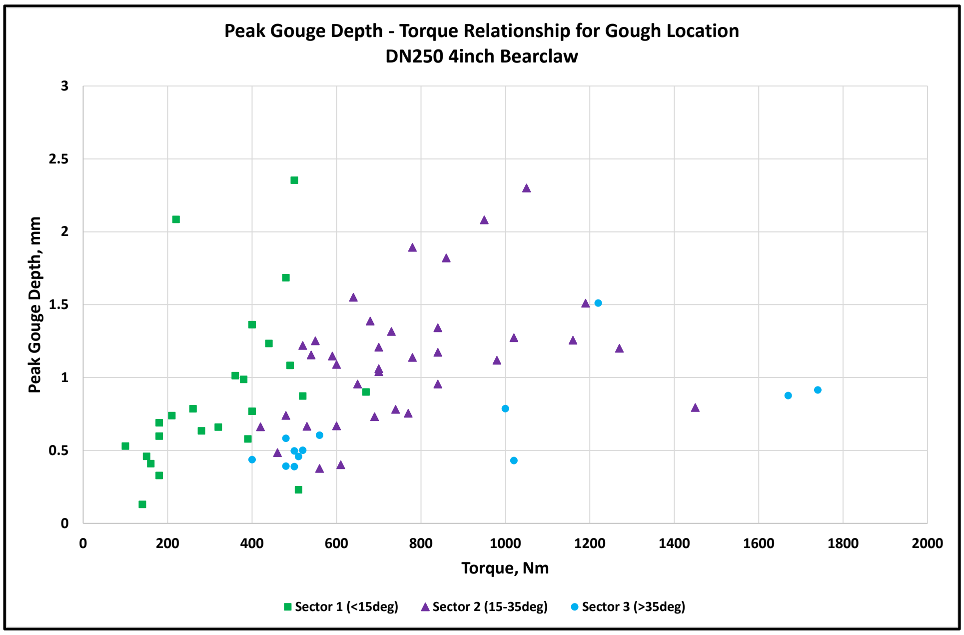


Figure 24 Influence of Gouge Position

The results show a strong correlation between peak gouge depth and torque for gouges within the same sectors and as the HDD tip moves further from the HDD-pipe axis centreline, the peak gouge depth reduces although the torque increases. For reference, the DN500 results shown in Figure 24 were all located within the 15°-35° sector. Hence, the variation of the gouge depths shown in Figure 20 can be partially explained by this effect.

6. CONCLUSIONS

The work outlined in this paper has been conducted to understand the nature of pipe damage caused by HDD equipment impacts on underground pipelines. A specially designed experimental rig that incorporates a full-size HDD machine has been designed and developed and has been used for this purpose. A series of experiments encompassing a range of key parameters including different lateral restraint conditions, HDD bit types and sizes of test pipe have been conducted.

The results show that the most common form of pipe damage is a series of gouges, aligned perpendicular to the axis of advance of the HDD bit. The maximum length of the gouges correspond to the diameter of the circle described by the HDD bit. The peak gouge depth was found to be highly dependent on the lateral restraint condition and to a lesser extent, the HDD bit type and size. The impact position on the pipe also appears to have an influence on the peak gouge depth.

A "Plough Force" term has been introduced which defines the tangential force applied by the HDD tip on the pipe. While the plough force is not a true representation of all forces acting on the pipe, since this also includes a thrust component, the term appears to be an appropriate parameter which can be used within a methodology to quantify the gouge depth. The work on the development of a HDD impact assessment methodology is still ongoing together with follow-up testing on other areas such as the impact of material grade and further assessment of the relationship between ground/soil types and lateral restraint conditions.

In addition, further analysis of the true forces acting on the pipe is still ongoing with the aim to develop generic pipe gouging models from the experimental results.

7. ACKNOWLEDGEMENTS

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