MTR Corporation Ltd

Commission of Inquiry into the Construction Works at and near the Hung Hom Station Extension under the Shatin to Central Link Project

Original Inquiry
Structural Engineering Expert Report

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1 Introduction

1.1 In May 2018 allegations were made in the media regarding potential defects in the rebar fixing works and deviations from the design in the Hung Hom Station Extension ('HUH') in Contract 1112 ('Project') of the Shatin to Central Link.

1.2 In July 2018 a Commission of Inquiry ('CoI') was appointed by the Chief Executive of the Hong Kong Government ('Government') to inquire into the facts and circumstances surrounding the diaphragm wall and platform slab construction works in the HUH and, in particular, the steel reinforcement fixing works, which raised concerns about public safety.

1.3 Subsequently, the scope of the CoI was extended by the Chief Executive in February 2019 to inquire into the facts and circumstances surrounding the construction works in other areas of the Project, namely the North Approach Tunnels ('NAT'), the South Approach Tunnels ('SAT') and the Hung Hom Stabling Sidings ('HHS') which also raised concerns about public safety or the quality of the completed works[1].

1.4 In light of these allegations, the MTR Corporation Ltd. ('MTRCL') proposed on 4 December 2018 that a holistic study should be conducted on the EWL, NSL and diaphragm walls in the Project to verify the as-constructed conditions and provide assurance on the structural integrity of the works[2]. The holistic study proposal was accepted by Government.

1.5 This holistic study proposed a three stage approach, as follows:

(i) Stage 1 – Desktop exercise

(ii) Stage 2 – Physical Investigation (Opening-up works)

(iii) Stage 3 – Design Analysis

1.6 Stage 1 was completed at the end of 2018 and included a number of assessment reports submitted to MTRCL by Arup, as well as work carried out by MTRCL's designer, Atkins, and its in-house teams.

1.7 Stage 2 commenced in early December 2018 and site work in terms of the opening-up to expose couplers was completed in April 2019. These opening-up works had two purposes:

(a) Purpose (i) – to inspect and verify the as-constructed steel rebar connection details of the EWL slab to address concerns arising from gaps in the

[1] See [AA1/1]
[2] See [B20/B26098-26136]

documentation or evidence concerning the connection between the EWL slab and the diaphragm walls; and

(b) Purpose (ii) – to randomly test whether the steel reinforcement rebars had been properly connected to the couplers at the EWL and NSL slabs connecting to the diaphragm walls.

1.8 Stage 2 also consisted of two further investigations, one of which involved conducting a suite of non-destructive tests to verify the condition of the concrete, the steel bar spacing, the coupler connections and to inspect the shear link placement.

1.9 Stage 3 commenced in early January 2019 and culminated in the publication of the Holistic Report in July 2019[3].

[3] See [OU5/3229-3350]

2 Instructions

2.1 I have been given and read the CoI's Directions on structural engineering expert evidence contained in the following emails from Lo & Lo:

(a) Email dated 29 August 2019[4];

(b) Email dated 20 September 2019[5];

(c) Email dated 12 October 2019[6]; and

(d) Email dated 25 November 2019[7].

2.2 I have also received a letter of instruction from my instructing solicitors, Mayer Brown, dated 5 December 2019, which confirms the instructions I had previously received concerning the preparation of this Report.

2.3 This Report responds to the redacted version of the Structural Engineering Expert Report produced by Mr. Nick Southward, Leighton's structural engineering expert, dated 11 October 2019 ('Southward's CoI 1 Report')[8].

2.4 I prepared this responsive Report in accordance with the CoI's Directions, in particular the following[9]:

"(a) the SE experts should focus on whether the as-constructed works are safe and fit for purpose from a structural engineering perspective; and only if they are considered not safe or fit for purpose that such experts should then provide their opinion on whether the suitable measures (as agreed in the Holistic Report or Verification Report, or subsequently) are necessary for safety from a structural engineering perspective; and

(b) the SE experts shall not be required to look into the question of whether the suitable measures (as agreed in the Holistic Report or Verification Report, or subsequently) are required for statutory or code compliance."

2.5 In order to provide context for my responses and to assist the CoI as much as possible in its consideration of those matters falling within its Extended Terms of Reference[10], I have considered it necessary and appropriate to include the following sections in this responsive report to provide a summary of the relevant parts of my First Report, the further work carried out since my First Report was prepared, and what I consider to be the appropriate Guiding Principles in terms of

[4] See [OU7/9691-9692]
[5] See [OU7/9968-9970]
[6] See [OU8/10561-10562]
[7] See [OU9/10978-10979]
[8] See [ER2/item 14.1]
[9] See [OU8/10561-10562]
[10] See [AA1/1]

considering and addressing problems similar to those which are presented by the Project.

3 First Report

3.1 My First Report was submitted to the CoI in January 2019, and formed the basis for my evidence given to the CoI back in January 2019[11].

3.2 My opinions as set out in the First Report were structured under a number of headings dealing with: Ductility and Mechanical Couplers; Rebar Detailing and Engineering Judgement; Percentage Strength Utilisation; Coupler Strength Characteristics; Structural Adequacy; Load Test and Opening-Up; and, finally, some Miscellaneous Matters, including honeycombing and inadequate grouting of gaps above walls and columns.

3.3 My First Report included reference to two independent studies I had made and the Stage 1 Assessment work summarised in the Arup Reports[12].

3.4 I made reference to the initial assessments of Area A, the Hong Kong Coliseum ('HKC') and Areas B and C. These assessments included a review of the design of MTRCL's designer, Atkins, supplemented by a spot checking analysis, which were carried out to ascertain the general utilisation levels of both the EWL and NSL slabs, their connection with the eastern diaphragm wall and a review of the BA14 submitted information for the perimeter diaphragm walls. This work did not include any comprehensive analysis modelling or any scrutiny of the large range of variations in geometry and the details of the various zones of the structure; in fact, at this stage it relied only on spot checks.

[11] See [ER1/item 6]
[12] See Arup's Stage 1 Assessment Report dated 9 November 2018 [B19/25114-25156] and Arup's Design Spot Checks for Diaphragm Walls – Plaxis Analysis dated 27 November 2018 [B20/26004-26048]

4 Work Undertaken since the Original Hearing

4.1 Since the conclusion of the Original Hearing, MTRCL with the assistance of its consultants and contractors has carried out the Stage 2 Opening-up Works and the Stage 3 Assessment Analysis[13].

4.2 The Stage 2 Opening-up Works related to: the planned testing of the engagement lengths of the coupler connections using PAUT techniques; the exposure of selected parts of the works to verify the construction related to the Contractor's Alternative Design; and, the exposure of the EWL slab soffit to verify the nature and extent of the shear link installation[14].

4.3 The Stage 3 Assessment Analysis work included the station box and covers Area A, the HKC and Areas B and C, as well as a separate study for the SAT, NAT and HHS[15].

4.4 The three principal areas of concern which remained after the Original Hearing were specifically included in the Stage 3 Assessment Analysis, namely:

- the extent, distribution and strength of partially engaged Coupler Connections;
- the strength of the joint zone, with particular reference to the horizontal Construction Joint within Areas B and C of the EWL slab to D-Wall connection on the east side of the station box; and
- the Shear Capacity of the slab structures.

4.5 The analysis of the opening-up works, particularly the PAUT results, both from the purpose (i) and purpose (ii) works as referred to in the Introduction above, has provided the basis for understanding the nature and extent of the coupler thread engagement in the works. In conjunction with the comprehensive coupler testing programme carried out by MTRCL, the opening-up work has provided a basis to establish an acceptance criterion for the safety of the coupler connections. My opinion as to the conclusions which can be drawn from this work, and my responses to Southward's CoI 1 Report, are set out in Section 7 below.

4.6 The opening up work to the soffit of the EWL slab has also enabled an assessment of the shear link provision in the slab to be made. My opinions on the shear strength capacity of the slab, and my responses to Southward's CoI 1 Report, are set out in Section 8 below.

4.7 The Stage 3 Assessment Analysis which was carried out by different consultants using different approaches has determined the range of percentage strength

[13] See [OU5/3229-3350]
[14] See [OU5/3246-3272]
[15] See [OU5/3273-3275]

utilisation of the various elements of the construction. The pattern of utilisations and the consequent conclusions as set out in the different consultants' studies are very similar, and reflect the findings of the earlier Stage 1 analyses. For the purpose of this responsive report, I shall adopt the utilisation levels ascertained by Atkins who are MTRCL's detailed design consultant for the Project.

5 Guiding Principles of the Assessment

5.1 There are many aspects of the design and construction of the HUH structure which are unusual and set it apart from other projects when considering its structural integrity and safety.

5.2 Few structures have been subjected to the degree of post-construction survey, inspection and opening up, or subjected to the sophisticated independent analysis and testing which has been carried out on the structures by a number of different parties. It is important to recognise that the findings which can be derived from these various activities have established a high level of assurance in terms of the safety of the structure, a fortiori given that none of the findings have exposed any fatal flaws in the construction, despite the analysis and testing being subjected to very high acceptance standards.

5.3 Notwithstanding, in my opinion the findings/conclusions which can be drawn from the independent analysis and testing which I have referred to above should not be regarded as setting new standards or in any way diluting the manufacturers'/suppliers' requirements for future projects, unless such projects have been subjected to the same intense post-construction scrutiny. To be clear, in my opinion, it would be unreasonable to extrapolate the findings/conclusions to which I have referred above to other projects, because of the unique set of circumstances surrounding the HUH structure.

5.4 In considering safety it must be recognised that there is a large difference between the levels of risk to be considered during the design and construction stages of any project and the post-construction stage. Taking an extreme example, the cost and programme risks reduce substantially as the project nears completion from a peak at the inception of the project to effectively zero at its completion. The same risk profile in my opinion applies to considerations of structural integrity and safety of the structure.

5.5 In the inception and design stages of a project, much is unknown as to the actual future construction loadings and sequence, material strengths and geometric accuracy. For this reason, the international codes and standards contain partial safety factors. These factors include for the extremes of the variations in the applied loads and "ignorance" factors – "ignorance" factors are intended to reflect the level of uncertainties in the assumptions made in the design and the sophistication of the analysis methods to be adopted, to mitigate these unknowns; for example, in BS8110:1985 these partial safety factors were described and defined. BS8110 was the code on which the HKCoP:2004 Structural Use of Concrete (‘HKCoP’)[16] is based.

5.6 In my opinion, the logical consequence of the substantial reduction in risk between inception and post-construction of a project is that the basis of assessment of the structure should recognise and take account of the fact that many of the safeguards and conservative assumptions included in the original design and construction no longer apply and should be relaxed. The reality of the situation is that the level of “ignorance” has greatly reduced and, hence, so should the partial safety and “ignorance” factors.

5.7 In stark terms, my opinion is that it is inappropriate to apply the same loading and material strength assumptions used at the inception of a project to its surveyed and tested post-construction condition.

Fitness for Purpose

5.8 In this responsive Report, I give my opinions in accordance with the CoI's Direction that “*the SE experts should focus on whether the as-constructed works are safe and fit for purpose from a structural engineering perspective*”[17]. In assessing whether the structures are “safe and fit for purpose”, in my opinion the important aspect to be satisfied is whether the as-constructed structure is capable of being used and function as a station safely and without any physical restrictions on its operations and as anticipated by MTRCL. In that regard, the structure should be durable, safe, have sufficient strength, and not deflect or vibrate beyond those limits expected for a station and provide adequate dimensional accuracy to enable the station to operate as intended.

5.9 So far as I am concerned, it is very important to emphasise that “fitness for purpose” should not be confused with “Compliance”. To be satisfied, “Compliance” requires the as-constructed works to be completed strictly in accordance with the contract specifications and requirements, irrespective of whether the specified requirement is necessary in terms of “fitness for purpose”.

5.10 A crude example of the difference between these concepts would be if the specification required 10 rebars to be provided in a particular element of the structure to satisfy a “one-size-fits-all” standard detail, whereas upon scrutiny of the particular detail in the context of the as-constructed structure it can be shown that only 5 rebars are required to satisfy the operational performance requirements

[16] See [H8/2818-3015]
[17] See [OU8/10561-10562]

of the station; the former is a "Compliance" requirement and the latter would be a perfectly adequate construction solution meeting the "Fitness for Purpose" test.

5.11 A further example would be a situation in which a pile has been installed outside of the tolerances required by the contract or the relevant code, with the consequence that it fails the "Compliance" requirement. Notwithstanding, in many instances the pile would be acceptable on a fitness for purpose basis in the light of a review of the actual circumstances of the pile's location in terms of its loading and the soil conditions in which it was installed.

5.12 In this responsive report, I make reference to Arup's Stage 3 Assessment Analysis[18] which focused primarily on considerations of strength and distortion, albeit that aspects of durability were also considered and reported on. In my opinion, the conclusion that can be drawn from this work is that the station structures are both fit for purpose and safe in the context of the above definition.

Compliance

5.13 In various parts of Southward's CoI 1 Report, Mr. Southward opines that the as-constructed works are "code compliant"[19]. Compliance can have many definitions, but for the purposes of this Report it has been taken to be the strict application of the HKCoP and those further requirements specified in the BD acceptance letters[20]. Compliance with the HKCoP Site Supervision and the Contract Conditions is not considered to be part of this structural engineering assessment of safety so I do not address such matters. For the reasons stated below, I disagree with Mr. Southward that the as-constructed works are compliant with the HKCoP and the other requirements specified in the BD acceptance letters.

Codes of Practice and Safety Levels

5.14 Codes of Practice are by their very nature conservative documents. They have to be robust enough to cover a very wide range of applications – they are in a crude sense prepared on the basis of "one size fits all". They are not a design manual. In fact, they are generally regarded as guidelines, and the foreword to the HKCoP clearly states this to be the case. I recognise, however, that there are situations where they become mandatory as, for example, where they form part of a contract or the basis of a particular approval, but this does not alter the fact that they are conservative documents.

[18] See [OU6/8580-8752]
[19] See [ER2/item 14.1]
[20] See [H9/3871-4053]

5.15 In many respects, in my opinion, some of the conservative provisions built into the HKCoP as well as into the initial design basis do not apply to the post-construction reality of the HUH structures because, and by way of examples only:

- there are aspects of the HUH structures which are at the extremes and possibly beyond the limits of what the HKCoP can reasonably be expected to cover;
- this is a completed structure which has been subjected to extensive surveys, investigations, opening-up works and material and component testing; and
- many of the partial safety factors which are built into the HKCoP should no longer apply to their fullest extent in a structural re-assessment context of a completed structure.

5.16 For these reasons, when considering the structural integrity and safety of the HUH structure it is excessively conservative to continue to apply the full provisions of the HKCoP. For a post-construction assessment it is in my opinion both logical and correct that the context of the individual clauses of the HKCoP are reviewed against the current technical knowledge which is available for consideration.

Engineering Assessment of Complex Problems

5.17 Engineering assessments, particularly of complex multi-faceted projects, are not purely mathematical exercises; in fact, they involve a rigorous first principle review of the information available, seek additional data in areas which appear to be inadequately explained, and finally make a judgement.

5.18 Also, although I am not a statistical expert, as an engineer I use statistics in some of the tasks required in conducting my work, and have an understanding of the fundamentals of statistics and the discipline required in gaining meaningful results.

5.19 Arup initiated/suggested the application of the Binomial Analysis in our early reports to MTRCL based on our experience of considering similar problems where a 'pass-fail' criterion can be applied to a consistent set of data[21].

5.20 In the case of the HUH structures my approach has been:

(a) to critically review the opening-up and testing data that has been produced through the various stages of the Holistic Studies;

(b) to consider the reports served upon and the expert evidence given to the CoI; and

(c) to make limited studies subsequent to the publication of the Holistic Report in areas where I do not agree with the conclusions being drawn, for example in relation to the coupler connection failure rate proposed for EWL

[21] See [B19/25137-25138]

Area A because the Holistic Report is premised upon considerations of "compliance" as opposed to structural safety and fitness for purpose.

5.21 The approach adopted for my assessment, which is of a forensic nature, is the same as I would carry out on any of my projects. It is a process of:

(a) looking at the physical activities involved to understand the origins and nature of the variations involved;

(b) independently assessing the data provided;

(c) weighing up the strength of comparative opinions/interpretations; and

(d) seeking any additional information which may be relevant.

6 Structural Engineering Expert Report by Mr. Southward dated 11 October 2019

6.1 Southward's CoI 1 Report considers and sets out his opinions on three specific elements of the works carried out on the Project which were of concern during the Original Hearing in January 2019, and which featured prominently in the Stage 3 Assessment Analysis considerations, namely:

- Coupler connections and engagement;
- Shear link reinforcement; and
- D-Wall horizontal construction joint.

6.2 After considering the information amassed as part of the Stage 3 Assessment Analysis, Mr. Southward concludes that the as-constructed structure is safe. This is a conclusion that I agree with, albeit there are some points of detail related to compliance that I would dispute.

6.3 In that regard, in agreeing with Mr. Southward's conclusion in terms of the safety of the as-constructed structure, I acknowledge that some parts of the works as constructed have been found not to conform to the contract specification or the statutory requirements in terms of, *inter alia*, the processes to be followed in relation to obtaining approval for the use of the works, and accordingly have been classified as 'Non-compliant'. Nevertheless, and as I have explained above, structures can be perfectly safe to be operated as well as being fit for purpose but also be 'non-compliant' in the sense aforesaid.

6.4 'Non-compliances' with the requirements of a construction contract are common and in my experience there are specific management processes within the contract to resolve them. In my opinion, the technical and commercial resolution of such 'Non-compliances' can only be achieved through the implementation, as necessary, of the formal contract procedures for dealing with such matters.

6.5 In the following sections of this Report I explain for each of the three elements of the work referred to above my reasons for supporting Mr. Southward's important conclusion on safety and, where relevant, my reasons for disputing his opinions on 'compliance'.

7 Coupler Connections

7.1 Section 6 of Southward's CoI 1 Report presents his evidence concerning the fitness for purpose and safety of the coupler connections in the HUH station box.

7.2 He also addresses additional issues related to the Contract Conditions, including the BOSA specification, compliance and 'suitable measures' which are outside the scope of my Brief, which is to give my expert structural engineering opinion on whether the construction of the HUH Station is fit for purpose and safe.

7.3 In general, I support the logic of his evidence, but there are points of detail on which I would disagree. These are whether the "safe" level of partial engagement of the couplers is 28mm or 32mm and some matters of interpretation of the expert statistical evidence which are not material to the overriding conclusion that the construction is fit for purpose and safe, although I discuss them in my evidence where appropriate.

7.4 I will include some further supporting evidence in terms of the fitness for purpose and safety of the HUH Station to that provided in Southward's CoI 1 Report. This supporting evidence is derived from information and data that was created during the Stage 2 and Stage 3 Holistic Study, but not considered in the determination of the appropriate coupler connection failure rate. It has particular relevance for EWL Area A.

Statistical Evidence and Engineering Judgement

7.5 As I have explained in paragraph 5.18 above, I am not a statistical expert, but as an engineer I use statistics in some of the tasks required in conducting my work, and I have an understanding of the fundamentals of statistics and the discipline required in gaining meaningful results.

7.6 It was against that background that Arup suggested the application of the Binomial Analysis in our early reports to MTRCL based on our experience of considering similar problems where a simple pass-fail criterion can be applied to a consistent set of data.

7.7 Reviewing the statistical expert reports submitted by Dr. Wells and Professor Yin, and their presentations and cross-examinations, it is apparent that there is little agreement between the experts in terms of the integrity of the sampling strategy and its execution, and the appropriateness of the statistical analyses employed, particularly as it applies to the EWL Area A coupler connections.

7.8 In my experience, this level of disagreement is not an unusual occurrence in such matters, and hence explains why as an engineer when considering complex engineering problems it is important to look beyond the presented statistics and consider from first principles the processes at work and the available information that may have been overlooked.

7.9 This is not an unusual situation for an engineer to be in, and as explained in paragraph 6.9.3 of Southward's CoI 1 Report, it is a central part of an engineer's training – assessing data and making a reasoned engineering judgement of the course of action to be taken.

7.10 In that regard, my approach has been to consider:

- the physical process of forming a coupler connection;
- the Stage 2 Opening-up sampling strategy and execution;
- the PAUT purpose (ii) data set, which I have reviewed;
- the evidence presented by Dr. Wells and Professor Yin; and,
- the additional information which is available, including the purpose (i) data, to make an engineering assessment.

The Coupler Connections are Fit for Purpose and Safe

7.11 I am in agreement with Mr. Southward that the elements of the construction which incorporate coupler connections are both fit for purpose and safe. A summary of my relevant conclusions is given below and the supporting evidence is identified and set out in the following sections of this Report:

(i) From the results of the extensive testing of the coupler connections by MTRCL and others[22], I am satisfied that a coupler connection with an engagement length of 32mm will achieve the full strength of the connection, and satisfy the full range of strength tests specified by the relevant code AC133.

(ii) I acknowledge and support the point that Mr. Southward has made in Sections 6.7 and 6.8 of his Report, viz. that 28mm engagement has been shown to satisfy the strength requirements of HKCoP and, indeed, the loads to which the connections will be subjected when in use. However, my selection of 32mm engagement is based on the fact that it has been shown beyond reasonable doubt to pass any test that can be sensibly applied, albeit I acknowledge that neither 28mm nor 32mm meet the contract requirements.

(iii) I also acknowledge that with one exception none of the tests which were carried out on the coupler connections satisfied the permanent elongation test of 0.1mm. However, it is important to note that the elongation test is not a strength test, and its impact on the fitness for purpose of those elements of the structure which incorporate coupler connections is not material, as discussed in Arup's Stage 3 Assessment Analysis Report

[22] See [OU6/8620]

Volume 1, Appendix C[23]. It should also be noted in this context that the 0.1mm limit in the HKCoP for the elongation test is the lowest limit found in international codes which contain such a test. In fact, generally these codes have much higher limits, especially when large diameter rebar is used, as is the case with the EWL slab coupler connections.

(iv) In his evidence Dr. Wells, Leighton's statistical expert, opined that the data for NSL and EWL comprised two sets of data belonging to a single family of data[24]. I support that conclusion on the basis of my observations of the similarity of the data distributions and consideration of the mechanical process involved in forming a coupler connection. I also note that Professor Yin, Government's statistical expert, was directed that the data belonged to different families[25]; he did not review that direction. See paragraphs 7.13 to 7.15 below.

(v) Consideration of the data should be on the basis referred to in sub-paragraph (iv) above – a single family of data. See paragraphs 7.13 to 7.15 below.

(vi) From the PAUT readings the percentage failure rate can be established for 32mm engagement, and by applying this failure rate to the calculated capacity of any connection a fitness for purpose strength can be established; for example, if the failure rate was 10%, then the fitness for purpose strength of the connection would be assessed as 90% of the calculated capacity.

(vii) Dr. Wells gave a pass rate of 89.8% (10.2% failure rate) for 28mm engagement based upon a single family of data[26]. The Arup assessment of the PAUT purpose (ii) results is given in their Stage 3 Assessment Analysis Report, Appendix C Section C3, which is reproduced as **Annex 1** in this Report. That assessment gives a pass rate of 90% (10% failure rate) for 28mm engagement and 88% (12% failure rate) for 32mm engagement based upon a single family of data. It follows that there is very close agreement between Dr. Wells and Arup so far as the pass rate is concerned for 28mm engagement.

(viii) Arup arrived at a 70% pass rate (30% failure rate) for 37mm engagement – see **Annex 1.** Dr. Wells proposes very similar figures depending on the assumptions he makes about "missing-values"[27].

(ix) A separate binomial analysis of the available data for the EWL Area A combining both the data gained from purpose (i) and purpose (ii) gives a pass rate of 72% (28% failure rate) for 37 mm engagement (for a one-sided connection), which is remarkably similar to that identified in sub-paragraph (viii) above. This is further evidence in my opinion that all the PAUT results can be considered as belonging to the same family

[23] See [OU6/8634-8635]
[24] See paragraph 3.4 of Dr. Wells' CoI 1 Report.
[25] See paragraph 1.2.1 of Professor Yin's CoI 1 Report.
[26] See paragraph 4.28 of Dr. Wells' CoI 1 Report.
[27] See Table 1 under paragraph 4.28 of Dr. Wells' CoI 1 Report.

regardless of whether the location is Area A or Area B or NSL or EWL. The details of this separate analysis are given in **Annex 2** to this Report.

(x) Taking account of the contents of sub-paragraph (viii) above, the equivalent pass rate for a two-sided coupler connection, as in Area A and the HKC, would be 49% (51% failure rate) for 37mm engagement: see paragraphs 7.33 to 7.36 below. Dr. Wells' analysis for a two-sided coupler connection using a Monte Carlo analysis, which is widely used in the industry, gave a pass rate of 53% (47% failure rate) for 37mm engagement[28]. See paragraph 7.34 below.

(xi) I recognise the controversy surrounding the validity of The Formula given in Appendix II to MTRCL's Report on Statistical Analysis for the Holistic Report[29], in particular on the small sample size – see paragraphs 7.18 to 7.28 below. To address the concern about the small sample size taken in Area A under purpose (ii), I have for the purpose of this Report carried out a separate analysis by using the wider data set for Area A provided by both the purpose (i) and purpose (ii) PAUT results. This analysis shows that The Formula predicts a pass rate of 53% (47% failure rate). See paragraphs 7.35 to 7.36 below.

(xii) The pass rates given in sub-paragraphs (x) and (xi) above show remarkably similar results considering the different analytical approaches which have been adopted. Consequently, I would suggest and, indeed, conclude that a pass rate of 49 to 53% (47% to 51% failure rate) is appropriate for 37mm engagement. See paragraphs 7.29 to 7.32 and 7.35 to 7.36 below.

(xiii) Adopting the same methodology set out in sub-paragraphs (ix) and (x) above, the pass rate for a two-sided coupler connection with 32mm engagement would be 77% (23% failure rate). See paragraphs 7.37 to 7.38 below.

(xiv) Since the fitness for purpose strength (i.e. the pass rate) of the coupler connections is greater than the strength required to resist the forces given by the Stage 3 Holistic Study analyses, the structure is shown to have a reserve of strength and is deemed structurally safe.

(xv) For the above reasons, I conclude that the coupler connections in all parts of the HUH Station are both fit for purpose and safe, including the EWL coupler connections in Area A.

7.12 In the following sections of my evidence I will explain the basis for the above statements and conclusions.

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[28] See paragraph 4.42 of Dr. Wells' CoI 1 Report.

[29] See [ER1/item 11.3]

Single Data Set – the Evidence in Support

The mechanical process involved in forming coupler connections

7.13 Coupler connections are widely used in the construction industry, and as such they may be considered as a standard product with an experienced workforce available to execute the construction thereof.

7.14 The formation of the connection is a mechanical process and, as with all such processes, there will be some variation in its application, particularly in terms of variations in the level of engagement of the rebar into the coupler.

7.15 Notwithstanding, it is a reasonable judgement to make that the variation in coupler engagement will be, in an engineering judgement context, for a particular site and conditions applying thereto the same throughout the construction process whether that be the EWL Area C or the NSL Area A and observation of the similarity in the distribution of the data from the NSL and the EWL supports that conclusion. This view of the matter is, I consider, also supported by the evidence from Dr. Wells[30].

Similarity of the data distributions

7.16 When viewed from an engineering view point, the tabulation of the PAUT results in **Annex 1** for the EWL and the NSL shows a close similarity in the distribution of the percentage pass rate and engagement length, particularly when the adulterated items referred to in paragraphs 7.23 to 7.24 below are removed. These PAUT results suggest, as one would expect having regard to the contents of paragraphs 7.13 to 7.15 above, that rather than being separate data sets they are just one set, and hence any collection of coupler connections regardless of location can be assumed to conform to the same distribution of the percentage pass rate and engagement length as set out in Annex 1 which provides combined NSL and EWL data.

7.17 This is of fundamental importance in considering the Issues surrounding the EWL Area A Couplers.

Stage 2 Opening-up Works

Sampling Strategy

7.18 Two sampling strategies were used as part of the Holistic Study:

- Purpose (i) which was focused on opening up particular parts of the works to verify that the works had been constructed in accordance with the as-constructed drawings. These samples were selected with no particular panels in mind, save that the samples came from the areas in which there

[30] See paragraph 3.4 of Dr. Wells' CoI 1 Report.

was less confidence in terms of the construction records that were available; and

- Purpose (ii) which was focused on establishing the quality of the installed coupler connections in the EWL and NSL slabs connecting to the diaphragm walls.

7.19 I understand that neither Dr. Wells nor Professor Yin had any involvement in the purpose (i) works.

7.20 The purpose (ii) sampling strategy that Professor Yin embarked upon was sound: if the purpose (ii) strategy has failings, they would be in the constraints that were externally imposed on Professor Yin, namely:

- That the NSL and EWL results belonged to different data families – Professor Yin did not question the direction he was given that they were to be assumed to be different[31]; on the other hand Dr. Wells considered them to be part of the same data family and, hence, they should have been considered as a combined data set[32]. In my opinion, and for the reasons I have explained and tabulated in **Annex 1**, I consider that it would be more appropriate to treat the NSL and EWL results as one family.

- That large areas were inaccessible and could not be included in the opening-up exercise[33] – this has led to an unfortunate lack of data in Area A. However, on the other hand the purpose (i) PAUT results for EWL Area A dominate that data set.

7.21 This focus on the purpose (ii) sampling is understandable in terms of primary statistical analysis. In my opinion, given the constraints mentioned above, a reference to the purpose (i) results in the statistical analysis would have provided a desirable reality check in circumstances where one is dealing with a very limited data set.

7.22 In this context, I consider it important to point out that although the methodology of sampling for the purpose (i) data is different from purpose (ii), in both cases the sampling was not predetermined in any way and hence from an engineering assessment perspective can reasonably be considered to be two data sets from a single data family.

Execution of the Sampling Strategy

7.23 It is worthy of note that Dr. Wells points to a number of aspects of the execution of the sampling from which he concludes that the total data set is not compatible

[31] See paragraph 1.2.1 of Professor Yin's CoI 1 Report.
[32] See paragraph 3.4 of Dr. Wells' CoI 1 Report.
[33] See paragraph 2.2.4(ii) of Professor Yin's CoI 1 Report.

with the principles required for the application of a Binomial Analysis. I understand that in reaching this conclusion he has in mind the following factors:

- The data set should comprise samples gained from the PAUT readings and not be adulterated by samples based on a different value basis, i.e. the physically measured samples[34];
- The inclusion of samples which were not part of the initially selected samples, e.g. the inclusion of an additional sample exposed during the opening-up works if unconnected, whereas other exposed but connected samples of couplers were not included. This introduces a negative bias into the data set;
- The discarding of a sample if a PAUT reading was not made despite the fact that the joint was actually seen to connected, whereas if the sample was seen to be unconnected it would be included. This introduces further negative bias into the data set, which Dr. Wells tried to mitigate by suggesting the use of "missing values"[35]; and
- There are also reports that samples with valid PAUT readings were rejected if there were too many threads exposed. Such data would have been valuable in constructing a continuous data set.

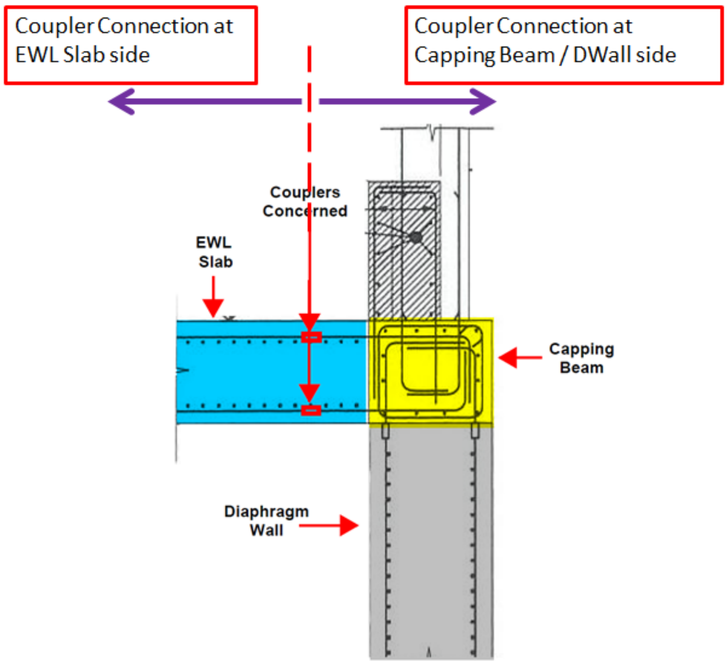
7.24 These adulterations undermine the purity of the purpose (ii) data set but, fortunately, can be shown not to be significant in an engineering context as shown by the analysis in Arup's Stage 3 Assessment Report, Appendix C3, Section C3.1, which is reproduced in **Annex 1** to this Report.

[34] See paragraphs 4.33 to 4.34 of Dr. Wells' CoI 1 Report.
[35] See paragraph 4.12 of Dr. Wells' CoI 1 Report.

EWL Area A/HKC Coupler Connections

Area A/HKC geometric arrangement and purpose (ii) Data Set

7.25 The connection arrangement in Area A and the HKC involves a two-sided connection as depicted by the figure below:



7.26 For the right-hand side, there were 2 failures from 11 connections identified during the purpose (ii) investigation. However, these results were based on a visual inspection of the number of threads exposed; there were no PAUT readings. This estimator of the pass rate, 82% (2/11) (18% failure rate), is significantly better than the estimator of the pass rate for the rest of the coupler connections, which is about 75% (44/180) (25% failure rate) for 37mm engagement.

7.27 For the left-hand side, PAUT readings were taken of 7 samples, of which 2 failed the 37mm engagement. A further 4 samples were exposed but discarded because PAUT readings could not be taken. Without including these discarded samples, the pass rate of the estimator is 71% (29% failure rate), similar to the rest of the coupler connections.

7.28 I recognise that these are very small samples, but these simple comparisons suggest that these connections should be at least equal in performance to the rest of the coupler connections and give rise to severe doubts concerning the 68% failure rate derived from The Formula.

Purpose (i) PAUT Data Set

7.29 The samples used for the purpose (i) investigation were selected with no particular panels in mind, save that they came from the areas for which there were the most limited construction records.

7.30 The majority of the PAUT records for "purpose (i)" were from Area A/HKC[36]. A summary of these "purpose (i)" records is:

- 20 sample records;
- 2 records have no PAUT and hence cannot be used to establish a statistical distribution, unless included as "missing values";
- Of the 18 records with PAUT, 11 records are in Area A or HKC; and

7.31 Of these 11 records there are none less than 41mm, i.e. no failures; by comparison, and as referred to in paragraph 7.27 above, the records used in the purpose (ii) statistical analysis were 7 records with 2 failures – a very substantial difference.

7.32 By considering the purpose (i) and purpose (ii) results as a single data set, the analysis of the resulting 4 failures from the 29 samples (2 failures from 18 samples on the left-hand side and 2 failures from 11 samples on the right-hand side) gives a pass rate of 72% for 37mm engagement which is very similar to the pass rate of 70% for the total purpose (ii) data set. The conclusion to be drawn from this analysis is that the coupler connections in EWL Area A are at least as strong as the rest of the coupler connections in the HUH structure, and hence should be considered to belong to the same data family. In that case, the pass rate for two-sided connections with 37mm engagement in Area A would be 49% (51% failure rate) which is derived from the 70% pass rate (for one-sided connections) in Arup's Stage 3 Assessment Analysis Report which is reproduced in **Annex 1**.

Reality Check by Reference to Dr. Wells' Approach and The Formula

7.33 In their evidence and presentations, Dr. Wells and Professor Yin both carried out a statistical analysis for 37mm engagement, but they did not carry out a calculation for two-sided connections at 28mm or 32mm engagement.

Dr. Wells' Approach

7.34 In considering the two-sided connection with 37mm engagement, Dr. Wells used a Monte Carlo model simulation, a recognised technique used in the construction industry for many problems. His analysis yields a pass rate of 53.3% (46.7% failure rate)[37]. This result is similar to the pass rate of 49% (51% failure rate) which is

[36] See [OU5/3318]
[37] See paragraph 3.5 and Table 4 under paragraph 4.42 of Dr. Wells' CoI 1 Report.

derived from the 70% pass rate (for one-sided connections) in Arup's Stage 3 Assessment Analysis Report which is reproduced in **Annex 1**.

The Formula

7.35 I recognise the controversy surrounding the validity of The Formula given in Appendix II to MTRCL's Report on Statistical Analysis for the Holistic Report[38], in particular on the small sample size – see paragraphs 7.18 to 7.28 above.

7.36 To address the concern about the small sample size taken in Area A under purpose (ii), I have for the purpose of this Report carried out a separate analysis by using the wider data set for Area A provided by both the purpose (i) and purpose (ii) PAUT results. This analysis shows that The Formula predicts a pass rate of 53% (47% failure rate). This result is also similar to the pass rate of 49% (51% failure rate) assessed by Arup (as referred to in paragraph 7.34 above), as well as Dr. Wells' Monte Carlo model simulation.

Pass rate for 32mm engagement in Areas A and HKC

7.37 The reality check in paragraphs 7.33 to 7.36 above confirms the soundness of Arup's statistical analysis.

7.38 As such, I rely on Section 8.3 of Arup's Stage 3 Assessment Analysis Report[39] and opine that the pass rates for 32mm engagement are:

- For a single-sided connection, a pass rate of 88% (12% failure rate) – see **Annex 1**; and
- For a two-sided connection in Areas A and HKC, a pass rate of 77% (23% failure rate).

Conclusions – Coupler Connections

7.39 For the reasons set out above, my conclusions on the List of Issues are:

Issue 1:

7.40 For structural safety purposes, what is the required minimum engagement length of threaded rebar into couplers? In particular, should the minimum engagement length (taking into account the allowable tolerance measurement of 3mm) be at least 37mm as set out in Section 3.3.13 of the Holistic Report?

Answer:

7.41 32mm – see sub-paragraphs (i) to (iii) in paragraph 7.11 above.

[38] See [ER1/ item 11.3]
[39] See [OU6/8620-8621]

Issue 2:

7.42 Based on the required minimum engagement length, what conclusions can be made about the number of defective coupler connections arising from the "Results of PAUT/Direct Measurement" in Appendix B3 of the Holistic Report?

Answer:

7.43 The number of defective coupler connections reduces (see the Table at **Annex 1**) with the consequence referred to in the Answer to Issue 3 below.

Issue 3:

7.44 Does the number of defective coupler connections have any impact on the structural integrity of the as-built works?

Answer:

7.45 No. The statistical or structural analyses carried out by Arup, Dr. Wells, Atkins and Mr. Southward all confirm that the fitness for purpose strength of coupler connections with 32mm engagement is such that the structure, including the EWL coupler connections in Area A, is structurally safe and fit for purpose from a structural engineering perspective, albeit that the coupler connection works are not in strict compliance with the HKCoP, the contract nor the statutory requirements in terms of, *inter alia*, the processes to be followed in relation to obtaining approval for the use of the works – see paragraph 7.11 to 7.38.

8 Shear Strength

Shear link investigation

8.1 Mr. Southward points out that the opening-up investigation to expose the shear links was carried out by creating an L-shaped excavation in the slab soffit. This is not an unreasonable approach as it has the advantage that it limits the area of concrete that has to be removed and thus also reduces the nature and extent of the damage to the structure. In my opinion, it is also likely that such a method of opening up the structure would expose the shear links that were anchored around the bottom slab rebar, albeit that I accept that exposure of all the potential shear link locations is not guaranteed.

8.2 By comparison, removing a square area of concrete is in my opinion unnecessarily invasive of the structure and results in more damage, albeit that it will confirm with certainty the provision (or otherwise) of shear link reinforcement anchored around the bottom slab rebar.

8.3 In the circumstances, my opinion is that the L-shaped opening up approach was appropriate, albeit that the width of the strips could in hindsight have been marginally wider to cover the extremes of link spacing.

8.4 I also consider that the investigation which was carried out was adequate in terms of providing an overview of the nature and extent of the shear link installation and revealed the range of non-conformities present for those shear links which were anchored around the bottom slab rebar.

8.5 However, the investigation could not be expected to expose those shear links that were anchored around the rebar at a higher level in the many layers of bottom slab rebar, which were up to 9 layers deep. Notwithstanding, the nature and extent of the investigation adopted was not, in my opinion, in any way unusual having regard to the massive concentrations of rebar which existed in the structure, both in terms of its spacing (nominally T40 rebar at 150mm centres in both directions) and the number of layers (up to 9 layers) which would have made breaking into the upper layers of rebar total impractical on any meaningful scale.

Shear Link Reinforcement

8.6 Section 7 of Southward's CoI 1 Report contains his evidence in terms of the fitness for purpose and safety of the shear link reinforcement used in the Project.

8.7 I support his conclusion that the as-constructed structure is fit for purpose and safe, on the basis, *inter alia*, of international codes.

8.8 I also support the logic of Mr. Southward's evidence and opinion, which is premised upon the following:

- illustrations and a description of what has been constructed;
- a discussion on constructability and detailing practice;
- a review of international and code requirements, such as Eurocode 2 and the American Association of State Highway and Transportation Officials' design code; and
- using various means to justify the shear strength of the construction.

8.9 The for-construction drawings[40] show a very substantial provision of shear link reinforcement throughout the structure which very comfortably exceeds the future demands of the structure in use. This means that there is a substantial reserve of strength which can be utilised to compensate for any failings in terms of workmanship, such as:

- The workmanship issues revealed during the opening-up of the EWL slab soffit, prompted primarily by insufficient records and photographs of the construction process - the links exposed during various opening up activities of the slab soffit showed the length of the horizontal tab to be 70mm for a 12mm bar, whereas the HKCoP standard requirement is 120mm – 10 bar diameters. This seems to have been a widespread practice across the site;
- the links in other locations were not of the correct diameters or spacing; and
- in some locations where there were multiple layers of bottom rebar, no links were visible.

8.10 With the exception of a few limited areas noted below, the insignificance of these non-conformities in the construction works has been demonstrated by the fact that it can be shown beyond any reasonable doubt that the structure has sufficient shear strength even in the absence of any shear link reinforcement by applying the strict interpretation of the HKCoP.

8.11 The safety of the construction can also be amply demonstrated by applying recognised international codes and standards. Mr. Southward presents a number of these in his report and the Arup Stage 3 Assessment Analysis Report, Volume 7 also describes how the shear strength of the structure can be demonstrated by using Eurocode 2 and the phenomenon of 'arching'[41].

[40] See Section 2.1 of the Arup Stage 3 Assessment Analysis Report, Vol. 7 [OU6/9609].
[41] See [OU6/9620-9623].

8.12 In conclusion, it is my firm opinion that the structure is fit for purpose and safe with regard to shear strength and there are a number of separate and distinct ways in which it can be demonstrated, including the following:

- By applying other recognised international codes and guidance, the limited number of areas yet to be accepted as passing the "compliance" test can be shown to be safe;
- The structure has shown no signs of distress and in comparison to the specified loadings used in the design, the actual future operational loadings are low;
- As explained in paragraphs 5.1 to 5.7 and 5.14 to 5.16 above, the approach taken in terms of load and material factors is very conservative when reviewing the safety of a structure post-construction;
- The for-construction drawings show a substantial over-provision of shear link reinforcement throughout the structure; and
- The actual strength of the concrete as shown by the concrete cube tests, and hence its shear strength, is greater than the design value and in my opinion should be used in any post-construction reviews of the safety of the structure.

Conclusions – Shear Strength

Issue 1:

8.13 What are your comments on the shear link investigation referred to in Sections 3.5.27 to 3.5.28 and Appendix B8 of the Holistic Report?

Answer:

8.14 Refer to paragraphs 8.11 to 8.15 above.

Issue 2:

8.15 What conclusions (if any) can be drawn based on this shear link investigation?

Answer:

8.16 As explained in paragraphs 8.6 to 8.12, the structure is safe and fit for the purpose, albeit the shear links are not compliant with the HKCoP , the contract nor the statutory requirements in terms of, inter alia, the processes to be followed in relation to obtaining approval for the use of the works.

9 Diaphragm Wall horizontal construction joint

Structural Integrity and Safety

9.1 In Section 9 of Southward's CoI 1 Report, in stating his conclusion that "The condition of the top of the East D-Wall at its junction with the EWL slab is of no structural concern, even if the worst possible assumption is made that there is a physical gap between these elements" i.e. it is safe, Mr. Southward draws attention to the large range of analytical work that has been carried out by MTRCL's designer, Atkins, as well as by the independent consultants, Arup and AECOM.

9.2 In support of Mr. Southward's conclusion as set out above, I consider it necessary and appropriate to confirm the conclusions that both I and my Arup colleagues have arrived at.

9.3 In my evidence at the Original Hearing in January 2019, I explained why in my opinion the structural integrity of the EWL Slab/D-Wall connection was controlled by the strength of the D-Wall and not by the strength of the horizontal construction joint. This has been demonstrated through the Arup Stage 3 Assessment Analysis[42].

9.4 Importantly, the integrity of the construction joint has been demonstrated beyond any reasonable doubt through calculations using simple models illustrating that dowel action or OTE thrust block action separately were capable of ensuring structural integrity across the construction joint. In addition, sophisticated non-linear finite element models have been used assuming a frictionless interface across the joint (in simple terms a gap) to demonstrate, again beyond any reasonable doubt, that the construction joint has an insignificant influence on the structural engineering performance of the EWL/D-Wall connection. The results of these calculations and analyses are described in the Arup Stage 3 Assessment Analysis Report, Volume 6[43]. Similar analyses have been conducted by Atkins, who has arrived at the same conclusion.

9.5 The analyses referred to above have also confirmed the views I expressed at the Original Hearing that the failure mechanism of the EWL slab to D-Wall joint zone is at the D-Wall connection with the soffit of the EWL slab[44]. It is also important to note that the D-Wall failure load is substantially greater than the maximum ultimate loads predicted for the EWL Slab/D-Wall connection by the structural analyses of the as-constructed structure as set out in the Stage 3 Assessment

[42] See Section 3.5 of Arup Stage 3 Assessment Analysis Report, Vol. 6 [OU6/9533].
[43] See [OU6/9521-9605].
[44] See Appendix C of my First Report [ER1/item 6].

Analysis. This provides yet further assurance of the large reserve of strength in the structure.

9.6 In my opinion, it follows indubitably from what is set out above that the structure is safe.

Workmanship

9.7 In Sections 8.2 and 8.3 of Southward's CoI 1 Report, attention is drawn to evidence of poor workmanship in forming the construction joint based upon some limited coring taken through the joint in panel EM94 which revealed the presence of remnants of hessian material as well as a clear non-conformity at the joint interface.

9.8 Mr. Southward is absolutely correct in stating that there is no sign of distress or movement at the construction joint in the cores taken at both panels EH-69 and EM-94[45], which statement is supported by the wider visual inspections of the structure. He is also correct to conclude that even if poor workmanship at the construction joint was more prevalent, the evidence from the various calculations and particularly the sophisticated analyses which have been carried out shows that the effect on the performance of the EWL Slab/D-Wall joint would be insignificant.

Rectification Proposals

9.9 I understand that all parties now recognise the compelling nature of the evidence concerning the reserves of strength at the construction joint and agree that any residual issue related to the construction joint is a workmanship matter. I reiterate that I agree with Mr. Southward that there are no strength or safety issues to consider.

Conclusions – Horizontal construction joint

Issue 1:

9.10 What are your comments on the results of the inspection of the horizontal construction joint at D-Wall panels EH69 and EM94 in Areas C1 and C2 as referred to in Section 3.5.34 of the Holistic Report?

Answer:

9.11 As reported in Section 3.5.34 of the Holistic Report, the two cores exhibit poor workmanship at the joint interface. Under normal circumstances these occurrences would raise a concern over the structural integrity of the joint.

[45] See Section 2.2.3 of Arup Stage 3 Assessment Analysis Report, Vol. 6 [OU6/9525].

9.12 However, inspection reports of the cores have indicated no movement at the joint and no distress has been noted in the surrounding structure.

9.13 In addition, as summarised in paragraphs 9.1 to 9.6 above, all the analyses carried out for this joint have shown conclusively that the integrity of the joint zone between the EWL Slab and the D-Wall is not reduced even if a physical gap is assumed along the construction joint. The structure is therefore safe and fit for purpose.

Issue 2:

9.14 What conclusions (if any) can be drawn from these results?

Answer:

9.15 The conclusion drawn from the inspections and Stage 3 analysis results is that the poor workmanship requires rectification.

10 Conclusions

10.1 Based on the contents of this Report as presented above, I conclude that the construction of the HUH station box has adequate reserves of strength and is both fit for purpose and safe.

11 Declaration

11.1 I declare that the contents of this Report are correct to the best of my knowledge, information and belief.

Mike Glover

6 December 2019

Annex 1

Extract from Arup Stage 3 Assessment Report Appendix C Section C3

A1 Introduction

The section below is an extract from the Arup Stage 3 Assessment Analysis Report, Volume 1, Appendix C, which includes adjustment for measured samples without PAUT results. If the effect of the additional adulterated items listed in paragraph 7.23 above are also included, for example, the removal of the additional unconnected bar samples and the direct measured samples without a PAUT reading, the pass rate for 37mm and 32mm engagement for EWL increases to 69% (from 68%) and 84% (from 82%). Including the 12 "missing values" for EWL has the effect of further increasing the pass rate, albeit by only a further 1%. The general observation to be made is that once a critical mass of data has been achieved and a stable distribution has been established, it takes a lot of contra-data to change the distribution.

A2 Acceptance Criteria

A2.1 Fitness for Purpose Acceptance Condition

Following from the results of the testing programme, the conclusion drawn is that a reasonable percentage 'pass' rate for the ultimate strength integrity of the construction with tension coupler joints would be that given for a 32mm (7 thread) engagement - an 88% pass rate, as shown by **Table 1**.

By selecting this lower average 'pass' rate of 88%, a reduction factor of 12% which is a more conservative position for the NSL slab which gives an additional level of confidence to this element of the works.

Table 1: Summary of Coupler Engagement Results

Engagement	NSL	%Passing	EWL (Note 2)	%Passing	EWL (Note 3)	%Passing	NSL+EWL (Note2)	%Passing	NSL+EWL (Note3)	%Passing
<28mm	3	92%	9	83%	9	83%	12	90%	12	90%
<32mm	4	91%	10	82%	10	82%	14	88%	14	88%
<34mm	9	84%	12	80%	11	80%	21	84%	20	84%
<36mm	17	74%	20	70%	18	75%	37	75%	35	75%
<37mm	23	67%	24	65%	21	68%	47	69%	44	70%
Total Sample	93		90		87		183		180	

Notes
1. The EWL Data includes 11 items deemed to have no PAUT reading of which:
   a) 3 bars which were cut and unconnected.
   b) 5 bars which were uncut and unconnected.
   c) 3 bars which were connected but removed by the Hong Kong Police Force and physically measured with engagement less than 40mm.
2. Of the bars in 1c) above to be more realistic in data analysis assume: 1 bar > 36mm, 2 bars > 34mm and 3 bars > 32mm.
3. The alternative approach is to disregard them from the data set below 37mm.
4. Coupler connections with 32mm engagement passed all tests, including cyclic and compression tests, and hence are equivalent to a fully engaged bar for ultimate strength assessments.

As set-out in section 8.3 of this report the reduction factors to be applied in the fitness for purpose assessment are restated in **Table 2.**

Table 2: Coupler Assembly Reduction Factors – Fitness for Purpose Condition

Reduction Factor	Area A	HKC	Area B	Area C
EWL	23%	23%	12%	12%
NSL	12%	12%	12%	12%

Annex 2

The binomial analysis referred to in paragraph 7.11(ix) of this Report

B1 Purpose (i) and Purpose (ii) Results in Areas A and HKC

The Tables below list the PAUT results for the purpose (ii) and purpose (i) opening-up work in Areas A and HKC for the left hand side of the EWL Area A coupler connection.

In Table 1, the 11 samples for purpose (ii) show 4 samples discarded, 2 unconnected and that 5 pass the 37mm engagement.

In Table 2, of the 20 specimens selected 12 of them are in Area A/HKC with the capping beam detail. These 12 results were located at the left-hand side of the coupler connection, and are highlighted in yellow. Apart from one sample that was discarded because a PAUT reading could not be made, the remaining 11 samples all passed the 37mm engagement.

From an engineering assessment viewpoint there are strong reasons for arguing that these purpose (i) results should be combined with the purpose (ii) Area A/HKC results, the more so since both data sets contain results from the same panel EH32. It is also noticeable that the data set from purpose (i) is larger than that for purpose (ii), and yet no account of the purpose (i) data was referenced in the analysis of the failure rate for the EWL coupler connections, or used as a reality check.

The data for the right-hand side of the connection was generated by visual examination based on the number of exposed threads. Of the 11 samples reviewed, 2 failed this test.

So, the full data set becomes:

- Left-hand side: 18 samples, 16 of which pass and 2 of which fail.
- Right-hand side: 11 samples, 9 of which pass and 2 of which fail.
- Total sample: 29 samples, 25 of which pass and 4 of which fail.

B2 Analysis Results

I understand that in terms of sample size, 29 samples is on the boundary of what is considered the minimum size to gain meaningful results from a statistical analysis.

On the basis that this sample size is just adequate, applying the above data to The Formula in MTRCL's Report on Statistical Analysis for the Holistic Report gives a pass rate of 53% (47% failure rate) for 37mm engagement. This is virtually identical to the result obtained by Dr. Wells using a Monte Carlo analysis.

A Binomial Analysis of the above combined data set would give:

- One-sided connection: 72% pass rate (28% failure rate); and
- Two-sided connection: 52% pass rate (48% failure rate).

The result for a two-sided connection compares very favourably with the 49% pass rate (51% failure rate) which is derived from the 70% pass rate for one-sided connections in Arup's Stage 3 Assessment Analysis Report which is reproduced in **Annex 1**.

Based on the distribution of pass rate relative to engagement length given by the Table in **Annex 1**, the corresponding conservative pass rate for a two-sided connection with 32mm engagement would be 77% (23% failure rate). This is much larger than any utilisation level given by the Stage 3 Assessment Analysis conducted by Atkins, and hence the HUH structure is shown to have a high reserve of strength and be fit for purpose and safe with regard to the coupler connections between the station box slabs and the D-Wall.

Table 1: Coupler Engagement Length Result for Purpose (ii) at EWL Area A/HKC

Item No.	Test Item Identity Mark	Panel No.	Enhanced PAUT Engagement Length (mm)	No. of Exposed Threads	Remarks	Result
12	EWL-W35-TT-T1-01-C1	WH35	NA	0	No valid PAUT result obtained & sample / result discarded	Discarded No. of embedded threads is not less than 8.
13	EWL-E32a(p2)-TT-T1-01-C1	EH32	NA	NA	Exposed rebar is unconnected to the coupler	Defective
14	EWL-E32a(p2)-TT-T1-02-C1	EH32	NA	NA	Exposed rebar is unconnected to the coupler	Defective
21	EWL-E40-TT-T1-01-C1	EH40	NA	9-10	Retrieved sample with direct measurement not less than 40mm	Not Defective
6	EWL-E40-TT-T1-02-C1	EH40	NA	10-11	No valid PAUT result obtained & sample / result discarded	Discarded
7	EWL-E40-TT-T1-03-C1	EH40	NA	11-12	No valid PAUT result obtained & sample / result discarded	Discarded
36	EWL-E32a(p2)-TT-T1-03-C1	EH32	44.4	0	-	Not Defective
37	EWL-E32a(p2)-TT-T1-04-C1	EH32	45.6	0	-	Not Defective
70	EWL-W35-TT-T1-02-C1	WH35	44.4	0	-	Not Defective
71	EWL-W35-TT-T1-03-C1	WH35	40.5	0	-	Not Defective
-	Extra sample on the EH40	EH40	-	-	No measurement was taken due to extra sample	Discarded due to no measurement

Table 2: Coupler Engagement Length Result for Purpose (i) at EWL

Item No.	Test Item Identity Mark	Panel No.	Enhanced PAUT Engagement Length (mm)	No. of Exposed Threads	Remarks
1	EWL-E33-TT-T1-02-C1	EH33	NA	0	No valid PAUT result obtained & sample / result discarded
2	EWL-E44-TT-T1-01-C1	EH44	NA	1-2	Retrieved sample with direct measurement not less than 40mm
3	EWL-E32-TT-T1-01-C1	EH32	44.5	0-1	Retrieved sample with direct measurement not less than 40mm
4	EWL-E44-TT-T1-02-C1	EH44	9.5	9-10	Retrieved sample with direct measurement less than 40mm
5	EWL-E32-TT-T1-02-C1	EH32	41.0	0-1	-
6	EWL-E32-TT-T1-03-C1	EH32	43.4	0-1	-
7	EWL-E33-TT-T1-01-C1	EH33	43.3	0-1	-
8	EWL-E35-TT-T1-01-C1	EH35	47.2	0	-
9	EWL-E35-TT-T1-02-C1	EH35	42.0	0-1	-
10	EWL-E35-TT-T1-03-C1	EH35	43.4	0-1	-
11	EWL-E36-TT-T1-01-C1	EH36	43.4	0-1	-
12	EWL-E36-TT-T1-02-C1	EH36	41.9	0-1	-
13	EWL-E37-TT-T1-01-C1	EH37	42.1	1-2	-
14	EWL-E37-TT-T1-02-C1	EH37	42.9	1-2	-
15	EWL-E46-TT-T1-01-C1	EH46	45.7	0-1	-
16	EWL-E46-TT-T1-02-C1	EH46	34.0	2-3	-
17	EWL-E69-TT-T1-01-C1	EH69	36.7	0-1	-
18	EWL-E69-TT-T1-02-C1	EH69	38.2	0	-
19	EWL-E72-BT-T1-01-C1	EM72	37.0	0-1	-
20	EWL-E72-BT-T1-02-C1	EM72	37.4	0-1	-