Real-time monitoring of a hybrid precast and in-situ concrete flat slab system

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ABSTRACT: This paper presents a scheme developed for instrumentation and monitoring of the structural performance of a hybrid precast and in-situ concrete flat slab system employed in an educational building. The system contains a precast plate flooring slab, which is composed of a thin reinforced concrete plate incorporating a steel lattice girder and all reinforcement required by design. A top mat of reinforcement is placed on site, as well as reinforcing stitching bars across the precast slab joints to ensure shear transfer and two way bending action. The concrete topping is then placed on site. Preliminary data obtained from the instrumented building are discussed. Continuous monitoring of the data will allow long term effects, such as creep, to also be monitored and compared with design guidelines.

KEY WORDS: Structural health monitoring; reinforced concrete flat slab; real-time monitoring; vibrating wire gauges.

1 INTRODUCTION

This project focuses on monitoring the structural performance of innovative building structural precast elements designed and manufactured by Oran Pre-Cast Ltd., and evaluating their effectiveness. This is done using vibrating wire gauges embedded in concrete elements of the newly built Life Course Studies Institute (LCSI) building at the National University of Ireland, Galway (NUI Galway).

At the first stage of the project, the vibrating wire gauges, as well as thermistors, were embedded in the concrete precast elements of the LCSI building. The structural monitoring started at the production stage of the precast elements, through the on-site installation and will continue during the building operation. Following this, measured data will be analysed and used to (i) develop and calibrate numerical models that predict building structural performance; and (ii) validate/develop design guidelines for hybrid precast and in-situ concrete flat slab systems.

This paper presents the instrumentation and monitoring strategy utilised to determine the structural performance of a hybrid precast and in-situ concrete flat slab system employed in an educational building, as well as some preliminary results from the project.

2 LIFE COURSE STUDIES INSTITUTE (LCSI) BUILDING

The construction of the LCSI building at NUI Galway commenced in July 2013 by JJ Rhatigan & Company Limited and is expected to be completed by May 2014. It was a design and build contract. The building was designed by Simon J. Kelly and Partners architects with Arup Consulting Engineers acting as consulting engineers and Alan Lipscombe as transport consultant. The building is part 3 storey and part 2 storey with a gross floor area of 3633 sqm (Fig. 1). It is predominately a precast concrete building with the precast elements designed, manufactured and installed by Oran Pre-Cast Ltd. The building will host the newly established Life Course Studies Institute (LCSI) and comprises of single occupant offices, open plan offices for researchers, a 150-seater lecture hall, and auxiliary spaces and services, including an atrium. The floor plate used for the superstructure of the building is a hybrid precast and in-situ concrete flat slab system. A reinforced concrete twin wall system is the primary lateral resisting system in the building, as well as transferring gravity loads to the ground. The twin wall system consists of two plates of 65mm thick concrete connected by means of cast-in lattice girders to form a core between the plates. The cavity between the plates is filled with concrete on site after the panel has been erected to complete the composite wall. Precast reinforced concrete columns and downstand beams are also employed in the building. A number of different cladding systems have been employed in the building, as seen, for example, in Figure 1.

Figure 1. Photomontage of the Life Course Studies Institute building © Simon J Kelly Architects.

3 INSTRUMENTATION OF THE LCSI BUILDING

3.1 Introduction

The scheme developed and implemented for the Life Course Studies Institute building is similar to that deployed in the

Engineering building at NUI Galway. Previous papers [1-5] have illustrated the overall instrumentation of that building and its development as a research tool. Lessons learnt from that project were taken forward into the new project. The vibrating wire (VW) strain gauges (Gage Technique model TES/5.5/T) embedded in the concrete elements in the Engineering building to monitor both temperature and longitudinal strains were found to be robust and reliable. Thus, these were also used in the LCSI building. The VW gauges have a range of greater than 3000 microstrain with a resolution of better than 1 microstrain. In addition to the VW gauges, a number of electrical resistance strain gauges were also installed on the reinforcement bars in the void form flat slab of the Engineering building. However, it was found that over time, the data obtained from these sensors may not be reliable due to the harsh environment that the sensors are located in. Thus, it was decided not to use this type of sensor in the LCSI building. In addition to the VW strain gauges (Fig. 2), a large number of thermistors were also embedded in concrete elements in the building, which will allow the influence of heat transfer and storage in structural precast building components on indoor environments to be investigated [6].

3.2 *Data acquisition system*

To collect data from the sensors, a data acquisition system containing CR1000 data loggers, AVW200 vibrating wire interface and AM16/32B multiplexers obtained from Campbell Scientific were employed. This system has been automatically logging data from the sensors embedded in the reinforced concrete flat slab system since their initial installation. During the construction phase, data is being stored on a flash memory card, which is manually downloaded onto a laptop weekly and backed-up on a server. However, data communication relay through the use of Campbell Scientific's NL115 Ethernet and Compact Flash Module will allow data to be collected over a local network after this is set up on commissioning of the building.

3.3 *Instrumented flat slab*

The 300 mm deep flat slab forming the first floor of the East block of the LCSI (Fig. 3) has a total of 59 vibrating wire (VW) gauges installed over 29 designated sections, as shown in Figure 4. The slab has a long span of 8.14 m and is the third bay out of a total of six in this direction (Fig. 3). It has two spans in the orthogonal direction of 5.808 m and 4.213 m with the outside edge supported on a 215 x 1180 mm deep downstand beam spanning between 800 x 215 mm precast reinforced concrete columns on grid line intersections and the interior of the slab supported by 600 x 215 mm reinforced concrete columns (Fig. 4). A plan view and typical cross-section indicating the locations of the VW gauges embedded in the concrete flat slab system are shown in Figure 4. The VW gauges are numbered in Figure 4, with 'Lx' and 'Ly' indicating strain measurements in the long and short span directions, respectively; 'H1', 'H2', 'H3' and 'P' indicating the depth within the slab that the sensor is located, as given in Table A1 in the appendix (i.e. near the top, middle, bottom of the in-situ component and plate, respectively). In total, 59 number VW gauges were employed. This includes:

- 10 no. on Grid Line 3 (centre of column strip) in the short span direction;
- 4 no. on Grid Line 3 + 1500 mm (edge of column strip) in the short span direction;
- 17 no. on Grid Line 3.5 (middle strip) in the short span direction;
- 9 no. on Grid Line A + 2800 mm (middle strip) in the long span direction;
- 4 no. on Grid Line B (centre of column strip) in the long span direction;
- 10 no. on Grid Line B + 1300 mm (edge of column strip) in the long span direction;
- 5 no. in the precast element located at in the longitudinal span direction at the edge of the column strip 1300 mm from Grid Line B.

Preliminary results from the sensors located on Grid Line 3.5 are presented in Section 5. However, in order to interpret this data, material properties are first required. These were determined through a material testing programme, which is described in Section 4.

Figure 2. Vibrating wire gauge installed in the plate element.

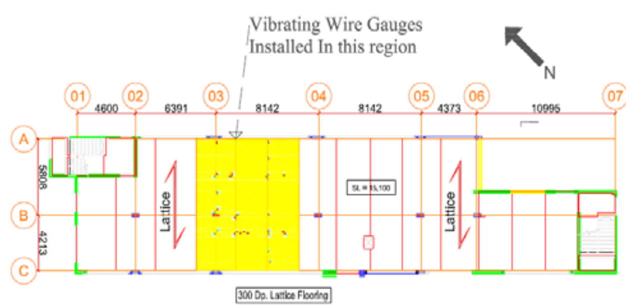

Figure 3. Plan of first floor of the East block of LCSI with instrumented area highlighted (dimensions in mm).

4 MATERIAL TESTING

In order to have accurate representation of the properties of the concrete used in the structural elements in this building, a comprehensive material testing campaign is currently underway. The data obtained for these tests will be used in interpreting the data from the sensors installed on site (see Section 3), in codified approaches and in material models employed in finite element analyses studies to determine the short and long term structural performance of reinforced concrete hybrid precast and in-situ concrete flat slab systems.

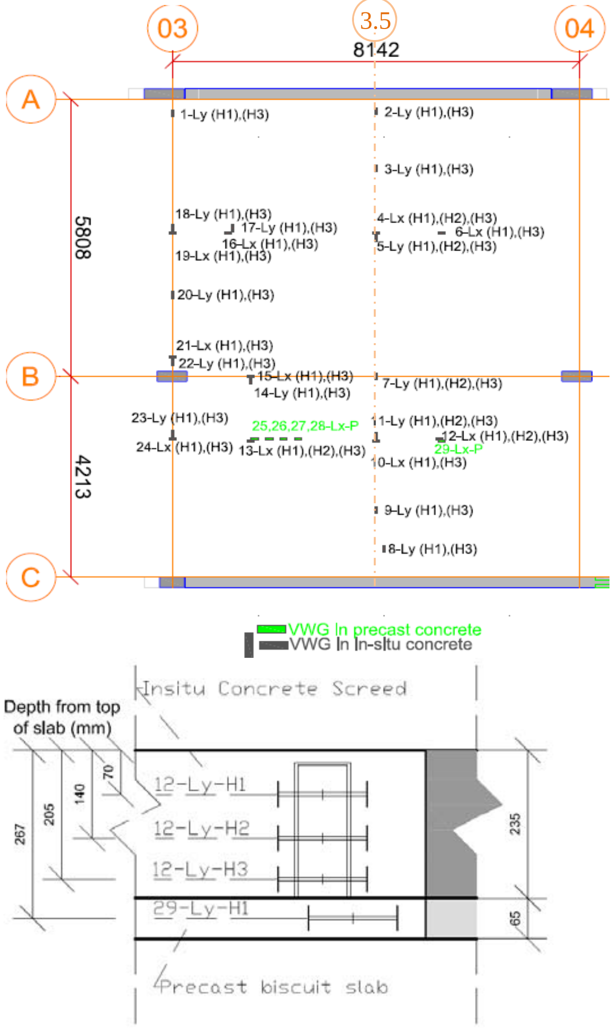

Figure 4. (a) Plan view and (b) typical section showing locations of vibrating wire gauge installed in the flat slab system (dimensions in mm).

Two mix designs were employed in the hybrid precast and in-situ concrete flat slab system – (1) a C40/50 D10 concrete mix with 370 kg/m^3 of CEM II-A/L for the precast plate and (2) a C28/35 D20 concrete mix (slump S2) with 195 kg/m^3 of CEM II-A/L and 85 kg/m^3 of (i.e. 30%) GGBS for the in-situ topping. Cylinder, cube and prism specimens were obtained from these concrete mixes to determine the various properties of the mixes used [7]. These included specific gravity, density, compressive strength [8], modulus of elasticity [9] and tensile strength of the concrete [10]. The tests have been/will be carried out at various concrete ages including 3, 7, 14, 28, 56, 112 and 365 days, as shown in Table 1. The coefficient of thermal expansion is also a useful property, which will be determined in the laboratory using the AASHTO T336-11 standard [11]. The apparatus used to measure this is shown with the calibration specimen in Figure 5. As a comprehensive material testing programme had already been undertaken on the concrete mix design for the precast plate element[12], a more condensed testing programme is undertaken in this project on this mix design.

Table 1. Testing schedule for Roadstone in-situ concrete mix

Materials testing carried out	100 x 100mm cubes	150 mm dia x 300 mm high cylinders
Compressive strength test (3,7,14,28,56,112, 365 days)	Y	Y
Tensile splitting test (28 days)	-	Y
Modulus of elasticity (7, 28,56, 112 days)	-	Y
Coefficient of thermal expansion (2 specimens)	-	Y
Specific gravity and density (All specimens)	Y	Y
Specimen left on site with embedded thermistor to measure temperature	-	Y

Figure 5. Apparatus used to measure the coefficient of thermal expansion.

The concrete compressive strengths for both the in-situ and precast concrete at different curing times, determined in accordance with IS EN 12390-3 [8], are given in Table 2. The 28 day minimum characteristic compressive strengths specified for both mixes have being met. The precast mix was specified as C40/50, but achieved average compressive cube strengths of 51.2 N/mm^2 and 71.9 N/mm^2 at 3 and 28 days of age, respectively. The associated characteristic cube strengths were 36.6 N/mm^2 and 60.5 N/mm^2, respectively. The associated characteristic cylinder strengths were 26.0 N/mm^2 and 43.5 N/mm^2, respectively. The in-situ concrete mix, specified as a C28/35, reached an average compressive cube strength of 40.9 N/mm^2 at 28 days of age. The associated characteristic cube strength was 30.2 N/mm^2, which is lower than the minimum value specified. On the other hand, the characteristic cylinder compressive strength was 29.8 N/mm^2 at 28 days of age, which exceeds the minimum value of 28 N/mm^2 specified. Figure 6 shows the development of the mixes' compressive strengths over time. The rate of strength gain between the cylinder and cubes for each mix is similar.

Figure 7 shows the development of the elastic modulus for both concrete mixes over time. The elastic modulus tends to an average value of approximately 45 GPa for both mixes. However, at 7 days of age, the elastic modulus of the precast concrete mix is approximately 40% higher than that of the in-situ concrete mix, as would be expected with its early compressive strength gain (Table 2). The different rates of elastic modulus development would have impacts in terms of stiffness and the deflections of the flat slab.

Table 2. Average compressive strength (N/mm^2) results

Specimen	Cubes		Cylinders	
Age (Days)	In-situ	Precast	In-situ	Precast
3	18.61	51.15	-	36.36
7	27.86	62.74	23.45	45.10
14	32.04	66.55	-	50.52
21	-	72.49	-	53.95
28	40.89	71.88	33.89	52.76
56	44.43	78.95	35.35	52.92
112	47.59	75.66	37.02	-

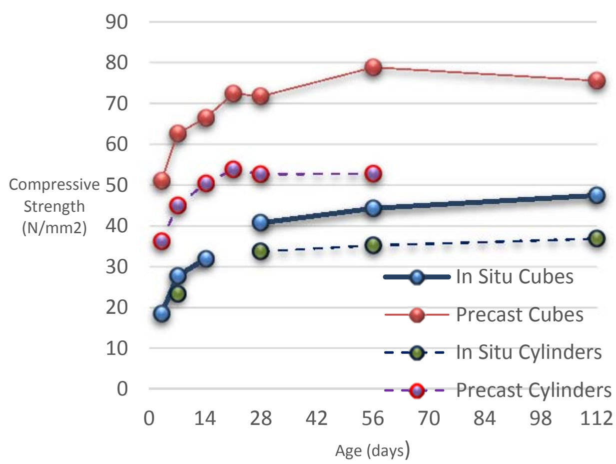

Figure 6. Development of average compressive strength with age

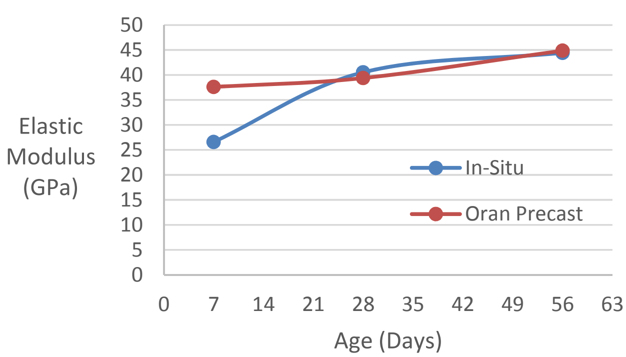

Figure 7. Development of elastic modulus with age for concrete mixes

5 PRELIMINARY RESULTS

The instrumentation installed in the LCSI building is generating real time data in relation to the strain and temperature in the first floor hybrid concrete flat slab system in the two storey section (East zone) of the LCSI building. The data will be analysed and interpreted continuously during both the construction and operational phase of the building. Unfortunately, no data was received from ten of the VW strain gauges. The majority of these gauges are located in the bottom of the in-situ element of the slab and it is suspected that they were damaged during the concreting operation. The location and reference for the installed VW gauges are given in Table A1. Two or three VW gauges (H1, H2 and H3) were located in the depth of the in-situ element of the slab to allow measurement of strain through the section to be recorded.

The 300 mm deep hybrid concrete flat slab at first floor consists of a 65 mm thick precast lattice girder plank and 235 mm thick in-situ concrete (Fig. 4(b)). The precast planks at first floor were installed on the 16-18th October 2013 and the in-situ concrete slab was poured on the 24th October 2013. Data relating to strain and temperature in the concrete slab has been continuously recorded since the 28th October 2013. The precast planks were propped prior to pouring the in-situ slab at first floor and subsequently a similar propping arrangement was used to support the roof slab overhead (similar hybrid concrete flat slab system). On the 3rd December 2013, props were removed from the roof slab first, followed by the first floor.

A number of load tests were undertaken on the first floor slab in late December 2013 and early January 2014 using bagged cement which was available on site, prior to fit-out. The load tests consisted of applying concentrated loads and uniformly distributed line loads similar to the design variable imposed load allowed for the slab (Figure 8).

Figure 8. Load test on first floor slab

The results presented in this paper are based on the VW gauges installed along Grid Line (GL) 3.5. VW gauges were installed at seven locations along GL3.5 and were positioned in both the long and short span directions. GL3.5 is located along the joint between two of the precast lattice girder units. All VW gauges have built-in thermistors, which monitor temperature in the concrete section. This is important as it ensures that the measured strain takes account of the difference in the coefficient of thermal expansion of the gauge and surrounding concrete. In the literature, there are varying recommendations for the coefficient of thermal expansion of concrete [13], [14]. The coefficient of thermal expansion is taken as 10 microstrain/°C, as specified in EN1992-1-1 [14] for the measured strains presented in this paper. It is envisaged that the proposed testing programme (described in Section 4) will determine specific properties related to the concrete, such as the coefficient of thermal expansion of the in-situ concrete in the floor structure and this will enhance the accuracy of the recorded strain data from the VW gauges.

The measured changes in strain through the in-situ section of the first floor structure along GL 3.5 (in the two-span direction) are shown in Figure 9. 'H1' and 'H3' refer to the first and third strain gauge at a specific location in the slab, measured from the top of the slab, respectively. The changes in strain relate to the period 28th October 2013 (commencement of recordings) until the 12th December 2013, which was 9 days after the props were removed from the first floor and the floor structure supported its self-weight. Until the props were removed, the floor structure was supported by five lines of continuous supports at maximum 2.4 m centres (as required by the precast lattice girder designer) and, therefore, it was expected that flexural strain in the slab would be limited. Prior to removal of props, the slab was subject to strain due to a number of factors such as creep, shrinkage (autogeneous and drying) and temperature change. The measured strains along GL 3.5 suggest that for the initial phase of curing (first 10 days) that the top portion of the slab (H1 gauges) was predominantly subject to tensile strains (negative) and the portion of the slab adjacent to the precast plank (H3 gauges) was subject to compressive strains. However, after the props were removed, the in-situ slab along GL3.5 was subject to compressive strains through the section. This suggests that the expected flexural strains along GL 3.5 are minimal and that the principal strains are from other sources other than flexure.

Figure 10 shows the measured change in strains through the in-situ portion of the slab at one location (gauge ref: 7-Ly) along GL 3.5 and the corresponding air temperature. The air temperature readings are from the NUI Galway weather station which is located approximately 1.5 km from the site [15]. The three strain measurements relate to gauges located approximately in the top (H1), middle (H2) and bottom (H3) section of the in-situ slab. The peak strains recorded in the three gauges correlate to the peak air temperature (12th December 2013), which suggests that strain due to temperature is a significant factor. It is also noted that following the removal of props, compressive strains are recorded at this location through the section of the slab, which indicates that flexural strains are not the dominant source of strain.

The prediction of strains (or deflections) for suspended concrete slab systems is difficult to estimate accurately. The behaviour of a slab at service loads varies with time and depends on the extent of cracking, stiffness of the slab, creep, shrinkage and degree of restraint. A range of +15% to -30% between calculated and actual deflections is suggested in some publications [16].

It is proposed to use BS EN 1992-1-1 [14] to determine predicted strains for the first floor slab in the LCSI building. Eurocode 2 [14] uses a distribution factor coefficient (ζ) to determine deformation parameters such as strain or curvature. The factor ζ allows tension stiffening at a section to be accounted for in calculations as the actual behaviour of a slab will be a combination of the member in its uncracked and fully cracked state.

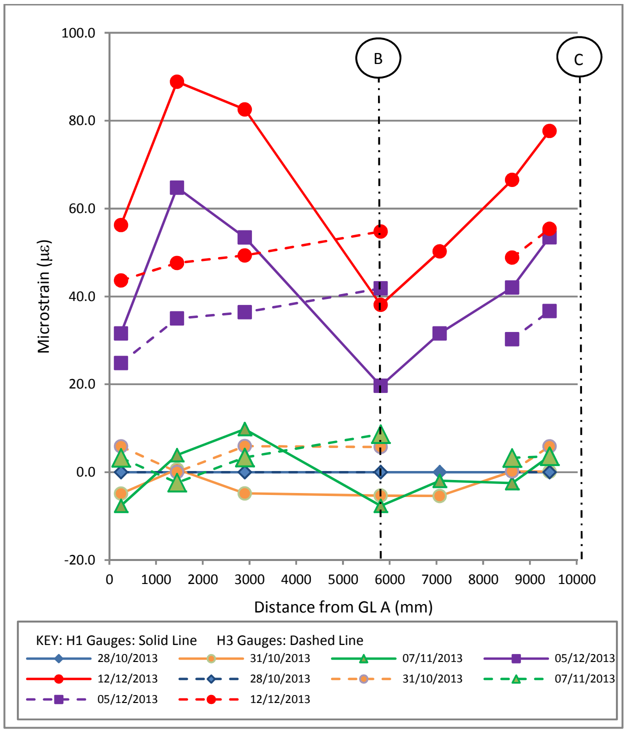

Figure 9. Changes in measured strain along GL 3.5

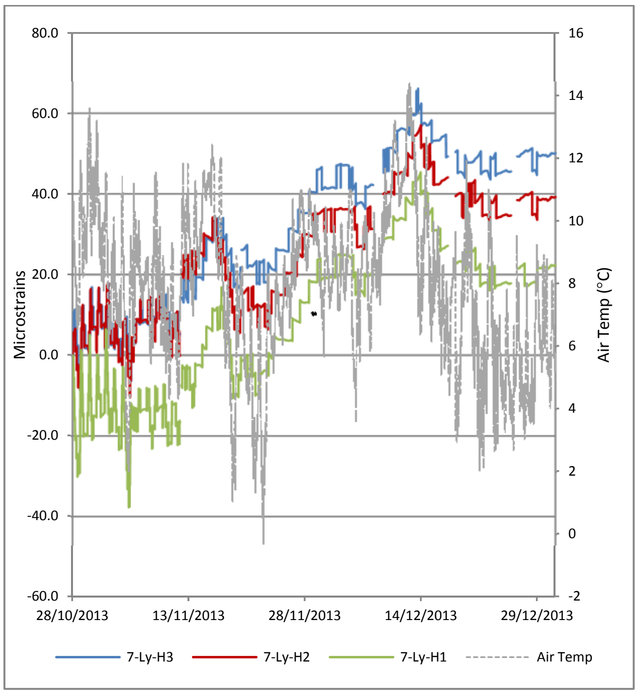

Figure 10. Measured strain (7-Ly) and air temperature

6 CONCLUSIONS

This paper presents a real-time monitoring campaign of a hybrid precast and in-situ reinforced concrete flat slab system installed in an educational building at NUI Galway. The preliminary results presented in this paper are at an early stage and it is expected that the measured data will be used to compare actual behaviour with predicted behaviour using structural codes, such as the Eurocodes. The material testing programme will complement this process because calculated methods for behaviour of concrete slabs at service loads are most sensitive to values of concrete properties (creep coefficient, elastic modulus etc.). Continuous monitoring of the data will allow long term effects in the structural performance of the slab to be monitored and compared with design guidelines.

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APPENDIX

Table A1. Location of VW gauges.

ID	X (mm)	Y (mm)	Z (mm)
1-Ly-H1	0	300	75
1-Ly-H3	0	300	187
2-Ly-H1	4071	250	67
2-Ly-H3	4071	250	180
3-Ly-H1	4071	1450	75
3-Ly-H3	4071	1450	207
4-Lx-H1	4071	2800	55
4-Lx-H2	4071	2800	110
4-Lx-H3	4071	2800	210
5-Ly-H1	4071	2900	60
5-Ly-H2	4071	2900	135
5-Ly-H3	4071	2900	200
6-Lx-H1	5371	2800	75
6-Lx-H3	5371	2800	190
7-Ly-H1	4071	5808	65
7-Ly-H2	4071	5808	140
7-Ly-H3	4071	5808	200
8-Ly-H1	4221	9421	50
8-Ly-H3	4221	9421	200
9-Ly-H1	4071	8621	75
9-Ly-H3	4071	8621	200
10-Lx-H1	4071	7171	65
10-Lx-H3	4071	7171	215
11-Ly-H1	4071	7071	70
11-Ly-H2	4071	7071	140
11-Ly-H3	4071	7071	205
12-Lx-H1	5321	7171	90
12-Lx-H2	5321	7171	125
12-Lx-H3	5321	7171	210
13-Lx-H1	1553	7171	85
13-Lx-H2	1553	7171	125
13-Lx-H3	1553	7171	205
14-Ly-H1	1553	5908	75
14-Ly-H3	1553	5908	205
15-Lx-H1	1553	5808	80
15-Lx-H3	1553	5808	200
16-Lx-H1	1103	2800	50
16-Lx-H3	1103	2800	200
17-Ly-H1	1203	2700	90
17-Ly-H3	1203	2700	200
18-Ly-H1	0	2700	70
18-Ly-H3	0	2700	205
19-Lx-H1	0	2800	75
19-Lx-H3	0	2800	185
20-Ly-H1	0	4100	75
20-Ly-H3	0	4100	205
21-Lx-H1	0	5400	80
21-Lx-H3	0	5400	210
22-Ly-H1	0	5500	80
22-Ly-H3	0	5500	200
23-Ly-H1	0	7021	70
23-Ly-H3	0	7021	195
24-Lx-H1	0	7121	70
24-Lx-H3	0	7121	205
25-Lx-P	1643	7121	267
26-Lx-P	1933	7121	267
27-Lx-P	2223	7121	267
28-Lx-P	2513	7121	267
29-Lx-P	5321	7121	267

Notes: 1) Depth (Z) measured from top of slab to centre of VW gauge.
2) H1, H2 & H3 refer to gauge at specific location measured from top of slab respectively. P refers to gauge in precast plank.
3) Origin taken as intersection of grid lines A and 3.