TECHNICAL MEMORANDUM

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BP Berau Ltd

CC Lidia Ahmad

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TANGGUH EXPANSION PROJECT – GROUNDWATER STUDY
PRELIMINARY ANALYSIS OF SUBSIDENCE DUE TO GROUNDWATER ABSTRACTION

1.0 INTRODUCTION

Golder has performed a preliminary settlement analysis to estimate potential ground subsidence at the Tangguh LNG facility site (refer to Figure 1) due to proposed groundwater abstraction from four proposed production wells. For this preliminary assessment, we utilised available data provided to Golder by BP together with details from the conceptual groundwater model and predicted groundwater level (head) changes over a period of 29 years (including 4 years construction plus 25 years operation) from the interim groundwater modelling carried out for the Tangguh Expansion Project – Groundwater Study. The settlement analysis is based on commonly adopted geotechnical engineering theory for calculating settlements due to a change in effective stress in the soil profile resulting from changes in aquifer and aquitard pore pressures.

Upon completion of the groundwater abstraction, groundwater levels and corresponding pore pressures should increase and hence cause a reduction in effective stress in the ground resulting in partial rebound.

2.0 BACKGROUND THEORY

Settlement occurs in subsurface soils due to changes in effective stress which, for this case, are induced by lowering groundwater pore pressures in both the confined aquifers and aquitards within the Upper and Lower Steenkool Formation. A reduction in aquifer pore pressures due to groundwater abstraction effectively increases the effective stress in these soil units resulting in settlement.

The settlement analysis has considered the compression in both aquifers and aquitards identified in the conceptual hydrogeological model for the site where the aquifers comprise relatively permeable sand or sandy silt layers, whilst the aquitards comprise lower permeability silt and clay layers.

The compression of soil layers as a result of lowering groundwater levels takes place in both the aquifers and aquitards; albeit compression in high permeability aquifers is typically simultaneous with pumping, whereas compression in low permeability aquitards takes place over a long period of time via consolidation settlement. The compression of the soil layers is calculated using a combination of elasticity and consolidation theory by application of the following formula:

$$\rho_{ult} = \Delta\sigma_v' \left(\frac{D}{E_0'}\right) \qquad (1)$$

where: ρ_{ult} = final compression or settlement

$\Delta\sigma_v'$ = increase in vertical effective stress

E_0' = stiffness of the soil in one-dimensional compression

D = thickness of a soil layer

The coefficient of volume compressibility (m_v) is commonly associated with and used for calculating consolidation settlement in with fine-grained soils such as clays and silts, and represents the compression of a soil, per unit of original thickness, due to a unit increase in pressure i.e.:

m_v = volumetric change / unit of pressure increase

The stiffness of fine-grained soils is therefore derived from m_v and total consolidation settlement calculated by the following formula:

$$\rho_{ult} = m_v \Delta\sigma_v' D \qquad (2)$$

The stiffness of coarse-grained (sandy) soils by direct application of E_0'.

Note that E_0' is the reciprocal to m_v (coefficient of volume compressibility) and is used in Equation (1) because the compression occurs in both fine-grained and coarse-grained soils.

Assuming no change in the unit weight of soil, the change in effective stress $\Delta\sigma_v'$ is equal to the reduction of pore water pressure $\Delta u = \gamma_w s$ (where γ_w is the unit weight of water and s is the drawdown). Therefore, Equation (1) can be rewritten as

$$\rho_{ult} = \gamma_w s \left(\frac{D}{E_0'}\right) \qquad (3)$$

The compression in a permeable aquifer, for all practical purposes, develops simultaneously with the drawdowns; whilst the compression in an aquitard occurs gradually over time depending on the consolidation parameters of the aquitard. The compression in an aquitard at time t after drawdown may be estimated by

$$\rho_t = R\rho_{ult} \qquad (4)$$

where R is the average degree of consolidation determined from time factor T_v and corresponding drainage conditions and distribution of pore water reductions. The time factor is calculated from

$$T_v = c_v \left(\frac{t}{h^2}\right) \qquad (5)$$

where h is the maximum drainage path length for vertical drainage within an aquitard and c_v is the coefficient of consolidation which can be expressed in terms of the aquitard properties as

$$c_v = k_v \left(\frac{E_0'}{\gamma_w}\right) \qquad (6)$$

where k_v is the vertical permeability of the aquitard.

The total settlement is therefore the sum of the compression in all aquifer layers and all aquitard layers.

$$\rho_{total} = (\rho_{ult})_{all\ aquifers} + (\rho_t)_{all\ aquitards} \qquad (7)$$

The settlement analysis details and results are outlined in the following sections. The rebound calculation following an increase in pore water pressure is basically a reverse to the settlement analysis, i.e. the amount of rebound is derived by subtracting the settlement at the end of pumping to the development of rebound calculated in a similar manner to that of settlement analysis.

3.0 METHODOLOGY

The following methodology has been adopted for the settlement analyses related to the proposed groundwater abstraction at the Tangguh LNG facility:

a) Develop a rationalised ground profile for the Tangguh LNG facility including all aquifer and aquitard layers based on the conceptual groundwater model developed for the Groundwater Study.

b) Due to limited geotechnical data specifically for subsidence calculation considering the proposed depth of the trial production well, the geotechnical profile and parameters were derived based on the following approach:

i) Adopt layers (aquifers and aquitards) from groundwater modelling considered being influenced by the pumping (water abstraction)

ii) Nominate points along and within the BP Tangguh property boundary

iii) Interpolate drawdown in upper and lower Steenkool aquifers from groundwater modelling to the nominated points and the wells locations

iv) Calculate change in stress from drawdown data

v) Adopt hydraulic conductivity values from groundwater modelling

vi) Calculate effective overburden stress (σ_{v0}') for all layers adopted in the subsidence calculation (water level assumed at the surface level)

vii) Estimate drained modulus of elasticity (E')

- For aquitards (fine-grained soils / clay)
  1) Estimate Overconsolidation Ratio (OCR) based on information from Calmarine (Nov 2000) geotechnical investigation report
  2) Calculate preconsolidation stress (σ_p') by multiplying OCR and effective overburden stress
  3) Calculate undrained shear strength using su/σ_p' = 0.25 relationship (Jamiolkowski et al, 1985)
  4) Calculate undrained modulus of elasticity (Eu) using Eu = 750xsu relationship (Burland, 1979)
  5) Calculate drained modulus of elasticity (E') using E' = 0.77xEu relationship (Wroth, 1972)
- For aquifers (coarse-grained soils/sand)
  1) Estimate E' using relationship E' = 4,600* z
     where z is the depth in meter and E' is in kPa unit (Terzaghi, 1954)

viii) Estimate c_v based on published data

ix) Adopt drawdown (ie. change in pore pressures) from the groundwater modelling results for the Upper and Lower Steenkool Formation aquifers to develop a profile of changes in effective stress distribution for each soil layer; i.e. over proposed abstraction period of 29 years.

c) Calculate settlement using Equation (7) for the resulting change (increase) in effective stress due to the lowering of groundwater levels at key locations including at the proposed production wells and within and around the Tangguh LNG property boundary.

d) Calculate rebound considering the subsidence model comprises over-consolidated soils, in which case the subsidence is primarily elastic or recoverable at the end of pumping; i.e. the inverse of settlement based in a similar rate of swelling on unloading as for consolidation on loading and assuming a 75% proportion of swelling to compression.

4.0 GEOTECHNICAL MODELLING

We have adopted a geotechnical model profile based on the conceptual groundwater model developed for the Tangguh LNG facility site combined with our estimation of geotechnical parameters for over-consolidated soils as shown in Table 1.

Table 1: Geotechnical Model and Parameters

Layer	Layer	Base Depth	Thickness	K_x K_y	K_z	E_0'	c_v
		m bgs	m	m/d	m/d	MPa	m^2/yr
Alluvial sediments	1	10	10	5.0	5.0	10	-
Upper Steenkool Formation – clay dominant	2	40	30	8.6×10^{-3}	8.6×10^{-4}	90	18
Upper Steenkool Formation – sand dominant	3	100	60	4.0	0.4	320	-
Upper Steenkool Formation – clay dominant	4	155	55	4.0×10^{-4}	4.0×10^{-5}	300	12
	5	210	55	4.0×10^{-4}	4.0×10^{-5}	310	
	6	265	55	4.0×10^{-4}	4.0×10^{-5}	410	
Lower Steenkool Formation – sand dominant	7	295	30	4.0	0.4	1,280	-
Lower Steenkool Formation – clay dominant	8	315	20	4.0×10^{-4}	4.0×10^{-5}	420	8
	9	340	25	4.0×10^{-4}	4.0×10^{-5}	450	

Notes: x,y indices denote properties in lateral direction and z index denote properties in vertical direction

Plate 1 depicts selected locations across the Tangguh LNG facility site adopted for the settlement analysis with change in effective stress derived from the drawdown interpolated from the interim groundwater modelling results as shown in Table 2.

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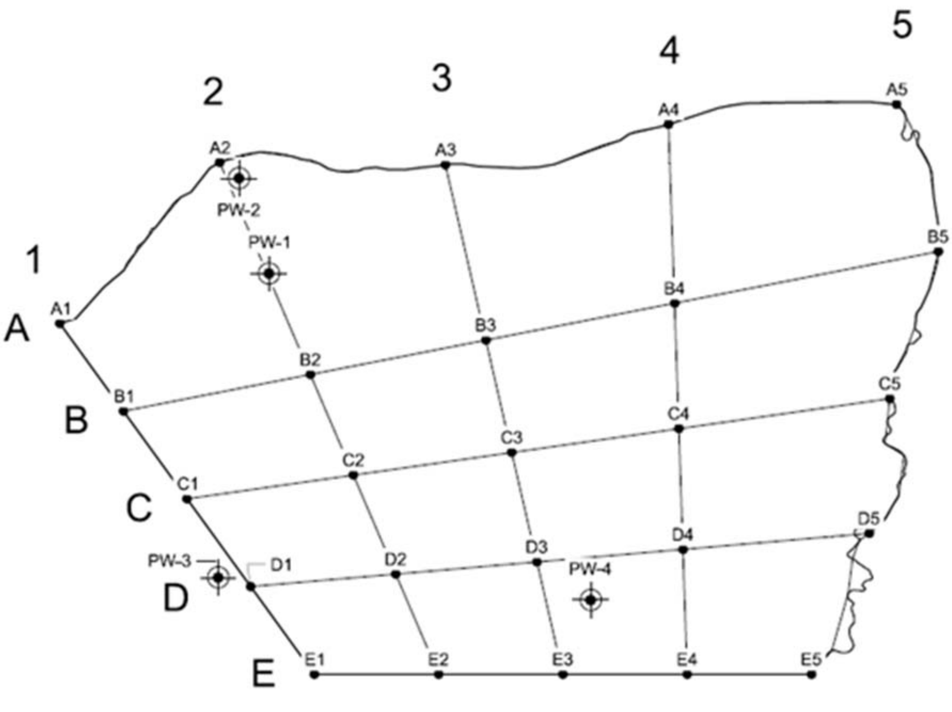

Plate 1: Selected Locations Adopted for Settlement Analysis

Table 2: Estimated Drawdown and Subsidence at Selected Locations

Point	Easting (m)	Northing (m)	Drawdown in Layer 3 (m)	Drawdown in Layer 7 (m)	Subsidence after 4 yrs (cm)	Subsidence after 29 yrs (cm)
A1	290099	9729057	0.18	7.1	0.7	2.1
A2	291548	9730515	0.10	9.8	1.0	2.8
A3	293593	9730495	0.08	7.1	0.7	2.0
A4	295614	9730862	0.06	5.3	0.5	1.5
A5	297680	9731044	0.04	4.2	0.4	1.2
B1	290676	9728260	0.28	7.8	0.8	2.3
B2	292369	9728592	0.15	8.9	0.9	2.6
B3	293959	9728904	0.10	7.5	0.7	2.2
B4	295669	9729239	0.07	6.0	0.6	1.7
B5	298058	9729707	0.05	4.4	0.4	1.3
C1	291252	9727464	0.20	8.5	0.9	2.5
C2	292759	9727679	0.14	8.4	0.8	2.5
C3	294194	9727884	0.10	7.5	0.8	2.2
C4	295708	9728101	0.08	6.5	0.6	1.9
C5	297617	9728374	0.06	4.9	0.5	1.4
D1	291829	9726667	0.16	9.2	0.9	2.7
D2	293143	9726780	0.12	7.9	0.8	2.3
D3	294423	9726891	0.09	8.3	0.8	2.4
D4	295745	9727004	0.08	7.0	0.7	2.0
D5	297430	9727149	0.06	5.2	0.5	1.5
E1	292405	9725871	0.11	7.4	0.7	2.2
E2	293531	9725871	0.09	7.1	0.7	2.1
E3	294657	9725871	0.08	7.5	0.7	2.2
E4	295783	9725871	0.07	6.6	0.6	1.9
E5	296909	9725871	0.06	5.5	0.5	1.6
PW 1	292000	9729500	0.13	15.0	1.5	4.3
PW 2	291720	9730370	0.10	15.0	1.5	4.3
PW 3	291897	9726940	0.17	14.0	1.4	4.0
PW 4	294916	9726542	0.09	13.0	1.3	3.7

Notes:
1. Layer 3 is Upper Steenkool Aquifer, Layer 7 is Lower Steenkool Aquifer
2. Construction Period of 4 years plus Operational Life of 25 years

5.0 SETTLEMENT ANALYSIS RESULTS

Settlement analysis has been conducted in accordance with the theory outlined in Section 2.0 and methodology outlined in Section 3.0. As described previously, the settlement analysis includes the compression both within the aquifers (Layers 3 and 7) and within the aquitards interfacing directly with the aquifers (Layers 2, 4-6 and 8-9) for the layers are listed in Table 1.

Note that based on the slimhole log it appears that there are multiple sandy layers intercalated within the clay dominant layers; however given the persistence of these sandy layers is not defined we have assumed two-way drainage and drainage path lengths of the order of 25-50% percent of the clay dominant layer thickness within the model for the consolidation settlement analysis.

The estimated subsidence due to groundwater abstraction after 4 years (end of construction) and 29 years (end of operation) at selected locations due to drawdown in the Upper and Lower Steenkool aquifers is also detailed in Table 2. Contours of estimated subsidence across the Tangguh LNG site are shown in Figure 2 which was developed based on subsidence at the selected locations from the settlement analysis.

Based on the groundwater modelling results we have assumed that the drawdown reaches its steady state condition after approximately 5 years and this time dependent change in stress was taken into account in the settlement analysis. Our consolidation settlement analysis using estimated consolidation parameters indicates that average degree of consolidation is about 90% at the end of pumping (29 years).

Plots of settlement over time at selected locations around Tangguh LNG site boundary are shown in Plate 2.

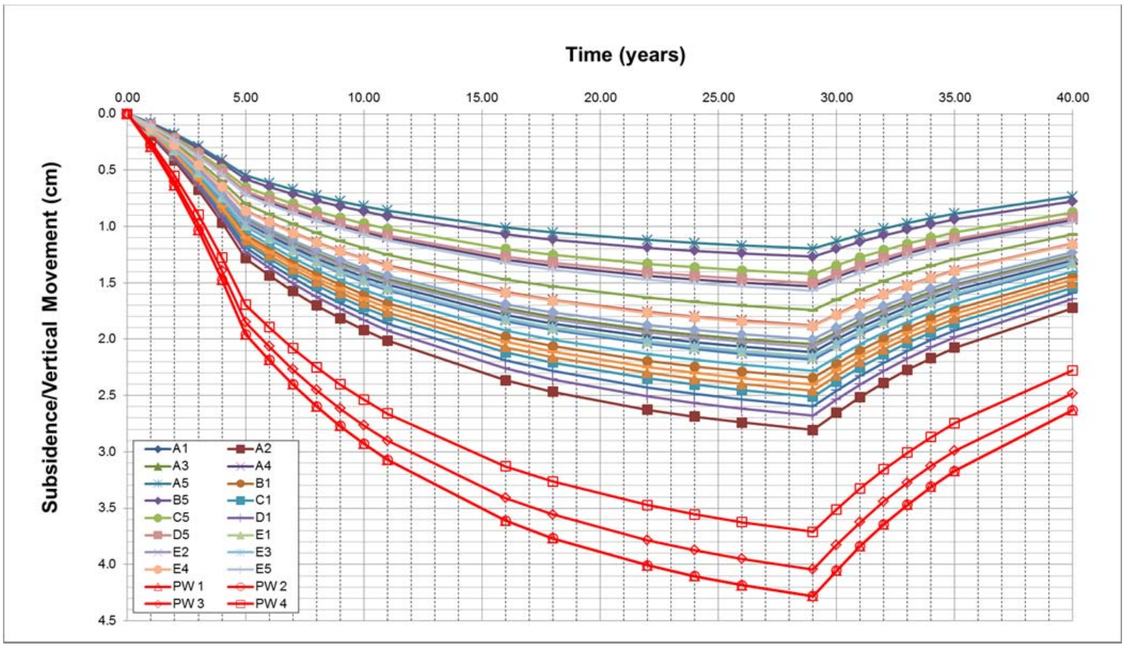

Plate 2: Time vs Settlement at Selected Points along the Tangguh Site Boundary and at Proposed Wells

It is anticipated that on closure (29 years) that groundwater abstraction will cease, hence pore pressures should rebound and reduce the effective stress within the ground which will also result in partial rebound. Plate 2 also illustrates the development of rebound following the cessation of groundwater abstraction from the four proposed production wells at the Tangguh LNG facility site.

Finally note that the subsidence modelling is based on the estimated drawdown contours and our evaluation is also necessarily based on a combination of assumptions, interpolations and engineering judgment given the lack of geotechnical data at depth; hence an effective subsidence monitoring program is recommended.

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BS/GEP/bs

6.0 REFERENCES

1) Preene M. Assessment of Settlements Caused by Groundwater Control*. Proc. ICE. Geotechnical Engineering*, 2000, 143, Oct., 177-190.

2) Powrie W. *Soil Mechanics: Concepts and Applications.* Spon, London, 1997.

3) Zhu G. and Yin J-H. Consolidation of Soil under Depth-dependent Ramp Load. *Canadian Geotechnical Journal*, 1998, 35: 344-350.

4) Cashman P. M. and Preene M. *Groundwater Lowering in Construction: A Practical Guide.* Spon, London, 2001.

Attachments:

Figure 1 – Site Plan
Figure 2 – Estimated Subsidence Contours Interpolated from Settlement Analysis at Selected Locations (29 years after Start of Pumping)

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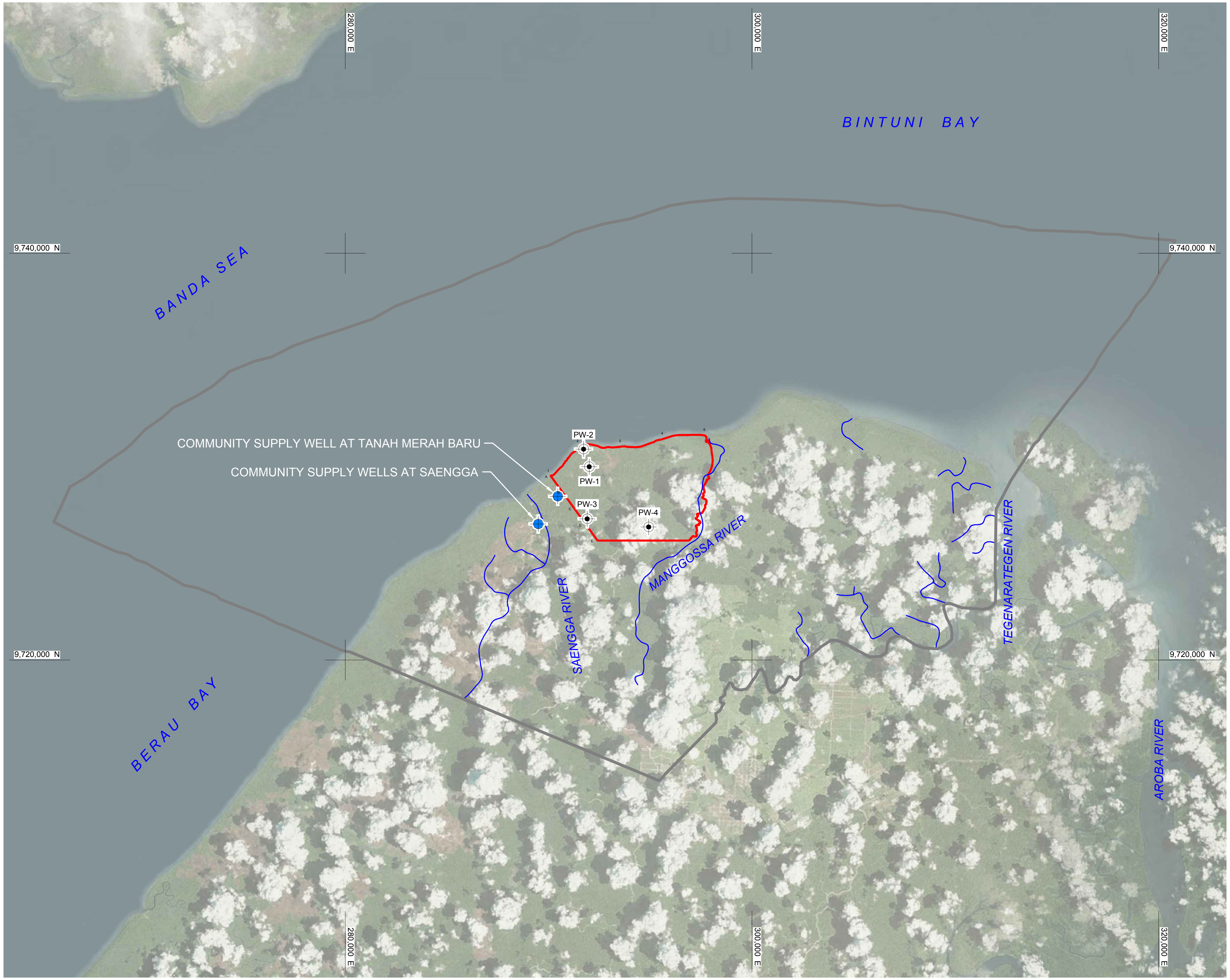

LEGEND

⌖	PUMPING WELL LOCATIONS
⌖	PROPOSED WELLS
—	RIVER
—	MODEL DOMAIN
▭	TANGGUH PROPERTY

NOTE:
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CLIENT BP BERAU LTD			PROJECT TANGGUH EXPANSION PROJECT - GROUNDWATER STUDY	
DRAWN BY DS	DATE 16.04.2014		DRAWING TITLE SITE PLAN	
CHECKED BY BS	DATE 16.04.2014			
SCALE AS SHOWN		SHEET SIZE A3	PROJECT No 138716004	DOC No 016 · DOC TYPE F · FIGURE No 1 · REVISION 1 · FIGURE 1

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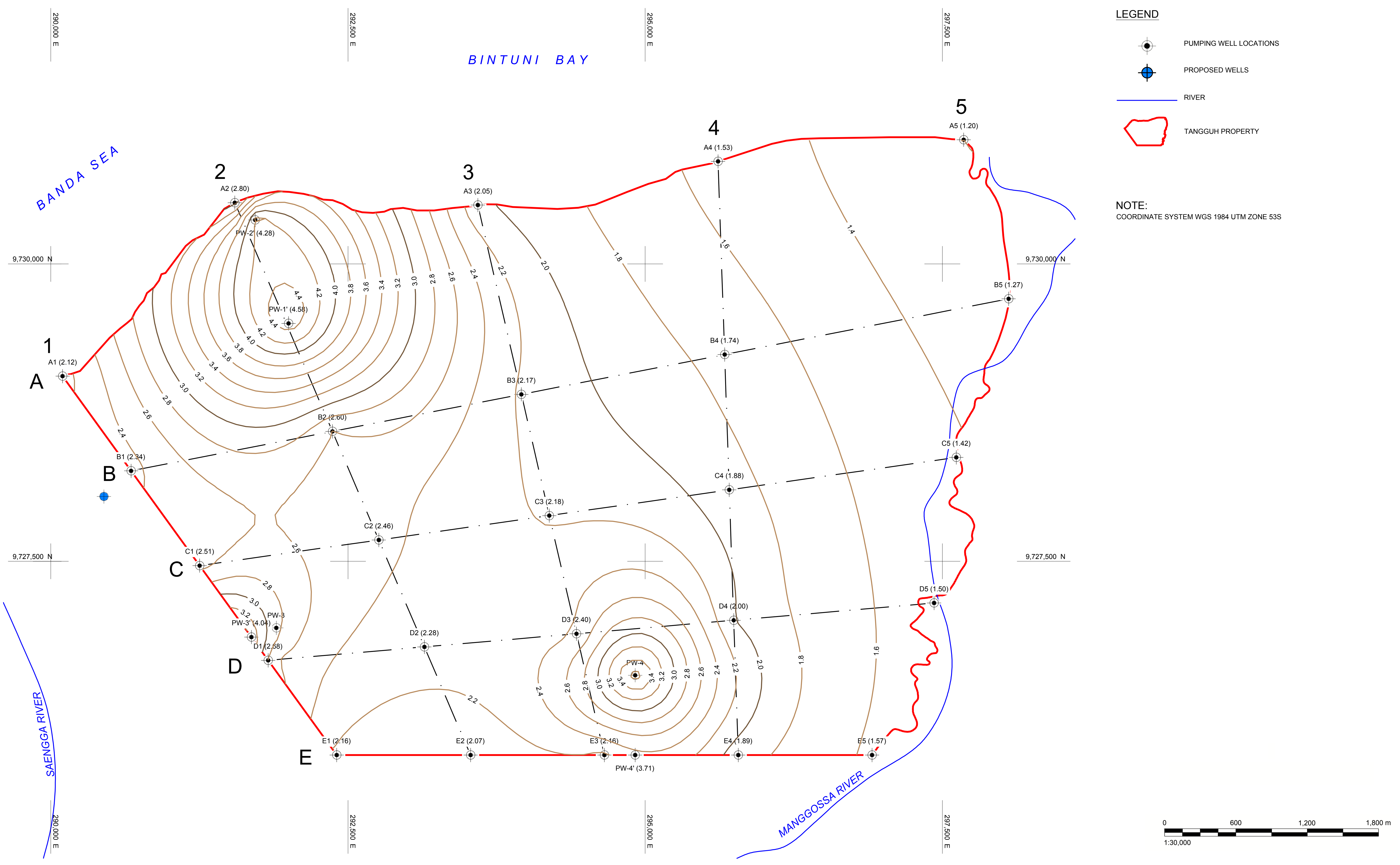

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DRAWN BY	DS	DATE	16.04.2014
CHECKED BY	BS	DATE	16.04.2014
SCALE	AS SHOWN	SHEET SIZE	A3

DRAWING TITLE
SUBSIDENCE CONTOURS INTERPOLATED FROM
SETTLEMENT ANALYSIS AT KEY LOCATION
(25 YEARS AFTER START PUMPING)

PROJECT No	DOC No	DOC TYPE	FIGURE No	REVISION	
138716004	016	F	2	1	FIGURE 2

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