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Dear Louise

**Lower River Murray – Tasks 8.2, 8.3 and 8.4/8.5 – Validity Period of Investigations and Influence of variation of soil parameters and site conditions on the potential for a River Bank collapse to occur.**

DWLBC commissioned SKM on 21 June 2010 to consider and respond to a range of hazard investigation questions relating to River Bank collapse and ongoing validity of the conditions found in the geotechnical investigations undertaken by SKM in late 2009 at 7 sites along the lower River Murray. It is understood that our responses to the Hazard Investigation Questions will assist DWLBC in providing advice to local government and the communities along the lower pool with regard to future river bank collapse.

We have separately advised the Factors of Safety applicable to the 7 sites for pool water levels ranging from -1.5m to +0.75m AHD for soil profiles and properties as assessed during the geotechnical investigations. This letter addresses the remaining queries from DWLBC as proposed by SKM and accepted by DWLBC for 5 of the 7 sites.

# 1. Validity Period of the 2009 Geotechnical Investigations

## 1.1 Context

Throughout recorded history, geotechnical investigations suited to available technology have been undertaken to aid design of many kinds of structures and their foundations and investigate slope stability. Modern codes of practice, including the Building Code of Australia, Australian Standards generally and ANCOLD, refer to Geotechnical Investigations as a requirement for approval of the design. The structures to which these investigations apply range from small and relatively light domestic buildings through institutional, commercial and major public works such as transport infrastructure and water supply dams, including earthworks in excavation and embankments, with project lives ranging from typically 50 years to one hundred years.

The validity period for geotechnical investigations therefore, is intended to be the design life of the asset and may potentially be less if in-situ conditions or assumed loadings change at the site.

## 1.2 River Bank Collapse Investigations

The 2009 site geotechnical investigations at river bank collapse sites along the lower River Murray may be reasonably considered to be valid for decades if there is no significant change in the soil parameters, geometry of the slopes or loading conditions. Furthermore, some other processes may result in the degradation of the soil materials and slope failure (i.e. earthquake, leaching, and change in soil fabric or vegetation) which are not easy to assess or predict a time span for the process.

The Factor of Safety (FoS) of a slope, as defined in previous reports, is the ratio of the net force resisting slope movement to the net force causing movement. When the FoS is one, these forces are exactly balanced; so, as a consequence, any slight overestimation in the net force resisting movement, or underestimation of the net force causing movement, could initiate slope failure. Any change to the net force causing or resisting movement will result in change in the factor of safety.

Choosing appropriate factors of safety for slope stability is based on several considerations such as uncertainties and nature of loadings, uncertainties and variability of thicknesses and slopes of soil layers, uncertainties in measurement and nature of soil strength in short term and long term loading situations, the adoption of a reasonable lower quartile strength envelope for the data, uncertainties in the failure mode, climatic effects which may affect the soil strength or geometry of the slope, redundancy in the failure mode, the consequences of slope failure and the cost of over-estimating.

For the lower River Murray river bank stability investigation, a long term FoS of 1.50 has been adopted as a minimum for slopes involving risk to assets or risk to life issues. However, risk assessments and cost estimates of potential remedial works to achieve the minimum FoS have not been carried out. Therefore, instead of investigating the various condition changes which affects the risk of failure of the river bank slope, a deterministic approach using a global FoS range has been adopted for this report as detailed below:

- $FoS < 1.0$;
- $1.0 \leq FoS < 1.50$; and
- $FoS \geq 1.50$

The most influential factors in assessment of the mechanical failure of the slopes are:

- Geometry of the slope
  - Width and slope of the riverbank's crest
  - Bank slope angle and shape (concave or convex)
  - Height of crest from toe and foundation
  - Length of slope exposed to environmental activities
  - Riverbed conditions that may induce scour at toe

  - Tension cracks in respect to edge of the river bank
- Soil layering system
  - Thickness and composition of layers
  - Alteration and sequence of the layers
  - Layering and interface slope
- Soil Parameters
  - Short term and long term strength of soil materials
  - Chemistry of soil materials
  - Stress history of soil materials
  - Moisture content and density of materials
  - Permeability
- Effect of Water
  - Level of the River – buoyancy and drawdown effects
  - Ground water level
  - Pore water pressure and seepage force
  - Flood levels and drawdown
- Loading conditions
  - Environmental and climatic activities
  - Human activities such as levees, marinas, jetties, buildings, roads, carparks.

Some of the influential parameters for the stability of the slope are time dependant (such as strength gain due consolidation under constant stress) but most of the variations in other parameters are due to environmental/climatic and human activities which are not time dependant (may happen any time over a short period) or are hard to estimate (meandering process of the river).

Furthermore, some of the processes may affect multiple parameters which makes the time estimation more difficult (if not impossible). For example differential settlement due to consolidation of the clayey layers with variable thickness may result in differential increase in strength but at the same time will change the geometry, layering slope and permeability of the layers. This may result in additional fill being placed on top of the crest to level the ground which will change the loading conditions. Furthermore, this differential settlement toward the river can cause tensile or shear cracking and allow water to enter the sliding mass.

A summary of the parameters and influential factors has been presented in **Table 1**.

It should be noted that sediment movement, riverbank erosion and meandering are long term natural processes which are heavily dependent on major flood intervals and management of river flows. As noted in previous reports, river banks are formed by sequential deposition of sediments under water in flow conditions much higher than currently being experienced resulting in metastable river banks when the flood waters recede. This process has resulted in deep soft impermeable clay beds as found extensively along the banks of the lower pool of the River Murray.

In **Table 1**, short term and long term are referring to the time scale of both applied action loads (or process) and ground response to the actions (i.e. failure or settlement). A few examples of the time scales are as follow:

- Dredging (short term) may result in change of geometry and failure (short term);
- Additional soil filling at the crest (short term) may result in consolidation (long term) and increase in undrained shear strength (long term); and
- Major floods will result in erosion of the bank slope or scour of the river bed at the toe (short term); however, the annual probability of the occurrence of this event is low (long term).

## Table 1: Summary of the influential parameters in the stability of the riverbank

| PARAMETERS | POTENTIAL INFLUENTIAL ACTIVITY / PROCESS | TIME SCALE | EFFECT ON THE FACTOR OF SAFETY |
|---|---|---|---|
| **Geometry of the Slope** | | | |
| Width and slope of the riverbank's crest | New developments (i.e. cut and fill)<br>Road construction<br>Settlement<br>Tension cracks | Short term<br>Short term<br>Long term<br>Short term | Significant |
| Slope angle and shape (concave or convex) | Settlement<br>Dredging<br>Erosion / Slumping<br>New developments | Long term<br>Short term<br>Long term<br>Short term | Significant |
| Height of slope from toe and foundation | Settlement<br>New developments (i.e. cut and fill) | Long term<br>Short term | Significant |
| Length of slope exposed to environmental activities | Settlement<br>New developments (i.e. cut and fill) | Long term<br>Short term | Insignificant |
| Riverbed conditions at toe | Erosion / Scour<br>New developments (i.e. cut and fill) | Long term<br>Short term | Significant |
| Tension cracks in respect to edge of the river | Moisture content change / Desiccation<br>New developments | Short term<br>Short term | Significant |
| **Soil Layering System** | | | |
| Thickness and composition of layers | Settlement<br>New developments (i.e. cut and fill) | Long term<br>Short term | Significant |
| Alteration and sequence of the layers | Leaching<br>Changes in soil fabric<br>New developments (i.e. cut and fill) | Long term<br>Short term / Long term<br>Short term | Significant |
| Layering and interface slope | Settlement | Long term | Significant |
| **Soil Parameters** | | | |
| Strength of soil materials | Consolidation<br>Soil improvement activities<br>Leaching<br>Changes in soil fabric | Long term<br>Short term<br>Long term<br>Short term / Long term | Insignificant |

| PARAMETERS | POTENTIAL INFLUENTIAL ACTIVITY / PROCESS | TIME SCALE | EFFECT ON THE FACTOR OF SAFETY |
|---|---|---|---|
| Moisture content | Rainfall<br>River level<br>Groundwater level<br>New developments | Short term<br>Short term<br>Short term<br>Short term | Insignificant |
| Permeability | Consolidation<br>Leaching<br>Change in soil fabric<br>Soil improvement activities | Long term<br>Long term<br>Short term / Long term<br>Short term | Insignificant |
| **Effect of Water** | | | |
| Level of the River | Seasonal change in the level of the river<br>Flood<br>Construction of new weir<br>Change in the river discharge regime<br>Change in the wind pattern | Short term<br>Short term<br>Short term<br>Short term<br>Short term | Significant |
| Ground water level | New development<br>New lagoons<br>Rainfall<br>Seasonal groundwater level change | Short term<br>Short term<br>Short term<br>Short term | Significant |
| Pore water pressure and seepage force | New development<br>Consolidation<br>Groundwater level change<br>Change in loading conditions<br>Change in drainage system<br>Rainfall | Short term<br>Long term<br>Short term<br>Short term<br>Short term<br>Short term | Insignificant |
| **Loading Conditions** | | | |
| Environmental activities | Vegetation<br>River discharge<br>Meandering<br>Erosion/Scour | Long term / Short term<br>Short term<br>Long term<br>Long term | Significant |
| Human activities | New developments (i.e. cut and fill)<br>New infrastructure and traffic change<br>Water level change | Short term<br>Short term<br>Short term | Significant |

## 2. Preliminary Consideration of Potential Remediation Options

SKM has undertaken a desk study into the sensitivity of the FoS against river bank collapse in the Lower River Murray, arising from variations in soil strength parameters and topographical site conditions generally, and at 5 of the hazard sites already investigated in particular.

For the soft clay soils encountered in the riverbank investigations to date, the critical soil strength parameter is the undrained shear strength ($S_u$) of the clay soils, which has been found to be very low, so low as to be difficult to measure in-situ or in the laboratory. Increasing the value of $S_u$ would increase the resistance of the river bank soil to collapse. **Section 2.2** below examines the sensitivity of FoS to increases in $S_u$ at each of the investigation sites.

The shape of the riverbank ~~onshore~~ above the water line to the crest of bank (the wetland plane) and offshore below the water line to the deep water channel is also critical to stability of the river bank. The bank profile and water level determines the distribution of driving and resisting forces that contribute to river bank collapse, so a potential method of stabilising the river bank is to apply a stabilizing mass, in the form of a rock berm, to the bank toe where the mass can most affectively resist sliding. This is examined in **Section 2.3** below for 5 of the investigation sites.

The nature, frequency and slope of sand beds in the bank serve to complicate the response of bank stability to rising and falling water levels, and are site specific.

### 2.1 Sites Included in this Study

The stability of river banks at the following previously investigated sites has been considered:

- South Punyelroo (SP)
- Caloote (CL);
- East Front Road (EF);
- Riverfront Road (RF) at Sturt Reserve; and
- Woodlane Reserve (WR).

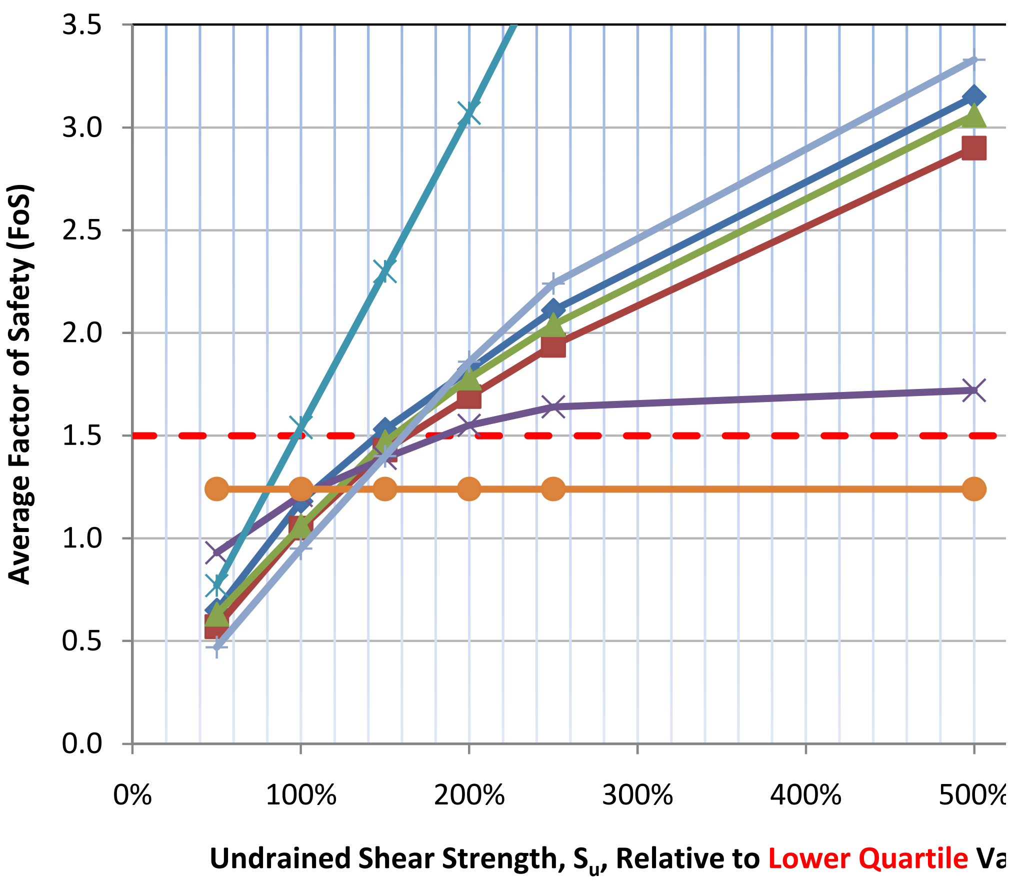
Swan Reach and Walker Flat were not included in this part of the study.

### 2.2 Sensitivity to changes in Undrained Shear Strength ($S_u$)

This component of the study was undertaken to assess the sensitivity of the FoS to the undrained shear strength of the clay layers. The aim was to identify the improvement in shear strengths (relative to existing strengths assessed from the geotechnical investigations in October 2009) which would be required for a FoS of at least 1.5.

The existing limit equilibrium models for SLOPE/W software (Ver. 7.16), which were developed for the river bank stability investigation, have been used for the study. The lowest river levels (identified through Task 8.1) were adopted for these analyses. The models were re-run with the undrained shear strength of all clay layers adjusted to 50%, 150%, 200%, 250% and 500% of the best estimate values.

The FoS results at the various strength ratios are summarised in **Figure 1**. In this figure, the vertical axis represents FoS and the horizontal axis is the undrained shear strength ($S_u$) of all clay layers as a percentage of the original values.




- **Figure 1: Summary of FoS at Investigated Sites for Various $S_u$ Ratios**

***Note to Figure 1:*** *The Factor of Safety (FoS) of a slope, is the ratio of the net force resisting slope movement to the net force causing movement. When the FoS is one, these forces are balanced; so, as a consequence, any slight overestimation in the net force resisting movement, or underestimation of the net force causing movement, could initiate slope failure. Therefore, for long term stability assessments, it is industry standard practice to set the minimum allowable FoS to 1.5 to allow for uncertainties in the estimates. Appropriate intervention is needed when FoS is less than 1.5. When the FoS is less than 1.3 there is a tendency for plastic movement to develop over time.*

The results of the analyses indicate that:

- Only South Punyelroo has a FoS above 1.5 for the current undrained shear strength of clay layers. This FoS falls below 1.5 if the undrained shear strength is less than 100% of the best estimate value.
- All other sites have FoS below 1.5 for the current undrained shear strength of clay layers.
- Clay undrained shear strengths of more than 150% of the ~~best~~ lower quartile estimate values are required to obtain an FoS of greater than 1.5 for Riverfront Road, Section1.
- Clay undrained shear strengths of between 150% and 200% of the lower quartile estimate values are required to obtain FoS of greater than 1.5 for all other sections except East Front Road Section 1.
- No increase in the FoS is obtained for East Front Road Section 1 with an increase in clay strength, as the lowest FoS failure is within the sandy material overlying the thin clay layer at this section.

***There is no natural consolidation or other process occurring currently, or expected in the foreseeable future, in the existing bank materials at the hazard sites investigated that would result in the significant increases in $S_u$ shown above to be needed to achieve satisfactory FoS values.***

## 2.3 Influence of Surcharging of Bank Toe via Stabilising Berms

This component of the study was undertaken to assess the effect on the FoS of constructing stabilising berms at the toes of the predicted failure surfaces. The aim was to identify if berms could be constructed to increase the FoS against failure to above 1.5.

The existing limit equilibrium models for SLOPE/W software (Ver. 7.16), which were developed for the river bank stability investigation, have been used for the study. The river levels for the lowest FoS (identified through Task 8.1) were adopted for these analyses.

For each section, stabilising berms were added to simulate placement of crushed rock. The berms were modelled with batter slopes of 2H:1V and 2.5H:1V. The berms were generally extended up to 50% of the failure surface height (i.e. generally 50% of the river bank height).

This analysis is not required for South Punyelroo where the existing FoS is greater than 1.5.

The FoS results for the two berm slopes are summarised in **Table 2**. Comments of the berm height adopted in the models are noted in this table.

- **Table 2: Summary of FoS at Investigated Sites for Various Stabilising Berms**

| Section | Berm Height | Factors of Safety (FoS) | | |
|---|---|---|---|---|
| | | No Berm | 2H:1V Berm | 2.5H:1V Berm |
| Riverfront Road 1 | 50% of Lowest FoS Slip Surface | 1.18 | 1.09 | 1.21 |
| Riverfront Road 2 | 50% of Lowest FoS Slip Surface | 1.05 | 1.11 | 1.16 |
| Caloote | 50% of Lowest FoS Slip Surface | 1.06 | 1.14 | 1.21 |
| Woodlane Reserve | 50% of Lowest FoS Slip Surface | 1.22 | 1.44 | 1.74 |
| East Front Road 1 | RL 0.50m AHD | 1.24 | 1.64 | 1.66 |
| East Front Road 2 | Top of Lower Bank (RL -1.23m AHD) | 0.97 | 1.01 | 1.03 |

The results of the analyses indicate that:

- The addition of a stabilising berm does not result in appreciable increases in FoS at Riverfront Road (Sections 1 and 2), Caloote and East Front Road Section 2.
- The addition of a stabilising berm results in increases in FoS at Woodlane Reserve and East Front Road Section 1 to above FoS 1.5.
- A 2.5H:1V berm with a height of 50% of the existing lowest FoS failure surface and 5m crest width results in a FoS of 1.74 at Woodlane Reserve. A FoS of 1.44 results with a 2H:1V berm. There is no increase in FoS if the stabilising berm crest width is increased to 10m instead of using a flatter berm.
- A 2H:1V berm extending from approximately RL -5m AHD (where the river bank flattens out) up to approximately RL -0.50m AHD results in a FoS of 1.64 at East Front Road Section 1. A reduction in the berm height by as little as 0.3m results in an FoS less than 1.5. There is no appreciable increase in FoS if a flatter 2.5H:1V berm is adopted.

Slope stability model outputs illustrating the cases summarised in **Table 2** are presented as **Attachment A**.

## 3. Timescale for Further Geotechnical Studies

Further Geotechnical investigation will aid the design of remedial works or the stability assessment of the riverbanks for any change in the existing conditions at the sites. It is expected that the following activities would benefit from additional geotechnical studies (stability assessment and/or site investigation):

- Stability assessment of the riverbank sections at sites other than those covered by the existing investigations or to extend and confirm conditions at existing sites; for example further investigations are warranted at Swan Reach where there is extensive deep river bank cracking upstream of the Waste Transfer Station site but no cracking downstream of the site;
- Assessment of the soil strength after remedial works such as chemical improvements, pre-loading and vertical drains;
- Assessment of the riverbank batter and toe for remedial works such as toe berm or piling;
- Assessment of soil strength gain due to consolidation where consolidation is considered to be possible; and
- Any new development on site such as levees, marinas, jetties, buildings, roads and car parks.

Except for the strength gain due to the consolidation or long term remedial works such as pre-loading, no specific frequency for the geotechnical investigations could be proposed as most of the conditions above are geometry or loading related which may be applied any time. Although after the change in geometry or loading, on-going geotechnical investigations or monitoring may be required.

On-going surveillance of the riverbanks is recommended as a vital tool for the monitoring of the failure risk. Monitoring should be focused on changes in the geometry or loading conditions of the riverbank slopes; as well as development or progress of crack behind the slope crest or on the batter.

## 4. Closure

The site specific elements of this study are limited to:

- The selected sites, because we do not have detailed stability modelling information at other locations; and
- The specified river level changes assessed in the study.

This study does not cover the effects of possible new shrinkage cracks due to groundwater level changes because these will be site specific and beyond the scope of a desk study. Existing failure modes have assumed tension cracks have developed at critical locations.

This study is intended to provide information on the feasibility of potential remedial works, and is not a design. Further analyses will be required if these or other remedial options are to be investigated in more detail.

In general, from the above and previous investigations, we conclude that:

- The unprecedented low river levels of 2008/9 served to highlight the long term pre-existing, natural, metastable condition of the river banks along the lower pool of the River Murray;
- There is no natural process for the weak clays along the riverbanks to develop significant increases in strength in the long term; therefore, raised and maintained high river levels will not generally improve riverbanks to acceptable FoS against collapse;
- The procedures implemented by DWLBC in 2009 to inform the community along the River of the dangers and symptoms (cracking) of river bank collapse are appropriate and likely to be the basis for long term monitoring and land use planning adjacent to the river for the local community;
- Remedial works to existing sites that have been closed due to bank instability would be intrusive and costly;
- Any land use development close to or on the river bank will need extensive and deep geotechnical investigations to properly characterise the site for consideration of the feasibility and design of the development; and
- On-going monitoring of the riverbank for deformation, development, environmental/climatic change and cracking is required.

Please do not hesitate to contact me should you require more information.

Yours sincerely

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**Attached**

Attachment A: Slope Stability Model Outputs