Structural Analysis of Foundation for Kazungula Bridge

1. Design of Substructure

1.1 Design Condition

1.1.1 Design Reaction of Superstructure

The Design Reaction of Superstructure is shown in Table 1.1.1.

- Rigid piers must resist all horizontal loads of the superstructure
- Movable piers must resist seismic load generated by each pier reaction

Table 1.1.1 Design Reaction of Superstructure (KN)

	A1 (A2)	P1 (P8)	P2 (P7)	P3 (P6)		P4 (P5)
Bearing Condition	M	F	M	M	M	E
Dead Load	6830	18000	18000	6830	8910	113400
Live Load	620	2800	2800	620	1400	2830
D + L Load	7450	20800	20800	7450	10310	116230
Horizontal Load (Earthquake)	680	4740	1800	680	890	12300

1.1.2 Condition of Substructure dimension

(1) P4, P5

- The pile cap soffit height is 926.600m which is water level with 2,000m3/sec discharges
- Embedment length into the fresh basalt is equivalent to pile diameter

These conditions are shown in Figure 1.1.1 and Table 1.1.2

(2) A1, A2, P1, P2, P3, P6, P7, P8

- The overburden on pile cap is more than 50cm
- Embedment length into the weathered basalt is equivalent to pile diameter

1.2 Proposal of Pile Diameter

(1) P4, P5

The comparison of pile diameter for P4 and P5 is shown in Table 1.1.3. The diameter 3.0m cast-in-place concrete pile is proposed because of economic and engineering advantages.

Table 1.1.3 Comparison of Pile Diameter (as pile length 18m)

		Pile Diameter (m)		
		2.0	2.5	3.0
Pile Cap Dimension (m)	Longitudinal	24.0	24.0	21.0
	Transverse	29.0	30.0	29.0
	Depth	4.5	4.5	4.5
Number of Piles		26	14	8
Quantity of Concrete (m3)	Pile Cap	2907	2888	2234
	Pile	1470	1237	1018
Ratio of Cost		1.12	1.09	1.00

(2) A1, A2, P1, P2, P3, P6, P7, P8

The comparison of pile diameter for A1, A2, P1, P2, P3, P6, P7, P8 is shown in Table1.1.4. The diameter 1.0m cast-in-place concrete pile is proposed.

Table 1.1.4 Comparison of Pile Diameter (as pile length 4.0m)

		Pile Diameter (m)			
		0.8	1.0	1.5	2.0
Pile Cap Dimension (m)	Longitudinal	6.0	7.0	7.0	9.0
	Transverse	12.0	11.0	11.0	11.0
	Depth	1.5	1.5	1.8	2.0
Number of Piles		18	12	6	4
Quantity of Concrete	Pile Cap (m3)	108.0	115.5	138.6	198.0
	Pile (m)	72	48	24	16
Ratio of Cost		1.02	1.00	1.08	1.26

1.3 Design of Pile

1.3.1 Design Model of P4, P5

The analytical model of pile cast-in-placed in weathered and fresh basalt is calculated as a pile supported by elastic springs. The pile top supporting condition has two types such as rigid and hinge.

1.3.2 Calculation Result

(1) P4, P5

Table 1.1.5 Calculation Result of P4, P5 (buoyancy neglected)

		Standard Loading	Earthquake Loading			
			Longitudinal		Transverse	
			Rigid	Hinge	Rigid	Hinge
Design Reaction	V (kN)	187403	184574	184574	184574	184574
	H (kN)	0	19417	19417	18517	18517
	M (kNm)	0	97274	0	171224	0
Coefficient of ground reaction (kN/m3)		60962	121924			
Ground bearing Capacity (kN)	Allowable	24074	36252			
	Force	23426	28603		30966	
Pull out Force (kN)	Allowable	-2376	-4026			
	Force	23426	17540		15177	
Bending Moment of Pile Section (kNm)		0	16082	24546	15323	23409
Re-bar Arrangement		52xD51 ctc 163				
Concrete Stress (N/mm2)	Allowable	8.0	12.0			
	Working	2.7	7.8	10.9	7.8	10.6
Re-bar Stress (N/mm2)	Allowable	-	300.0			
	Working	-	12.7	68.3	4.1	49.9
Displacement (mm)	Allowable	15.0				
	Working	0	8.6		8.2	

(2) A1, A2, P1, P2, P3, P6, P7, P8

The calculation result of P6 is shown in Table 1.1.6 as a typical pile foundation of the approach span bridges.

Table 1.1.6 Calculation Result of P6 (buoyancy neglected)

		Standard Loading	Earthquake Loading			
			Longitudinal		Transverse	
			Rigid	Hinge	Rigid	Hinge
Design Reaction	V (kN)	30135	28115	28115	28115	28115
	H (kN)	0	2719	2719	2719	2719
	M (kNm)	2288	30772	0	33598	0
Coefficient of ground reaction (kN/m3)	sandy soil(1.5m)	24316	48631			
	sandy soil(2.0m)	60789	121578			
	hard rock(1.0m)	121578	243156			
Ground bearing Capacity (kN)	Allowable	2820	4240			
	Force	2601	3670		3476	
Pull out Force (kN)	Allowable	-308	-557			
	Force	2421	1016		1209	
Bending Moment of Pile Section (kNm)		-	2351	2074	976	699
Re-bar Arrangement		12xD22 ctc 183				
Concrete Stress (N/mm2)	Allowable	8.0	12.0			
	Working	-	9.1	6.5	10.3	3.8
Re-bar Stress (N/mm2)	Allowable	200.0	300.0			
	Working	-	13.4	40.9	195.6	20.1
Displacement (mm)	Allowable	15.0				
	Working	0.3	4.0		2.5	

1.4 Condition of Foundation at the Main Pier

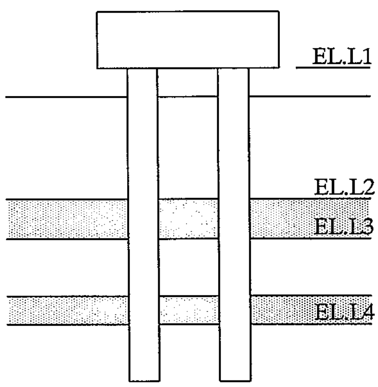


Figure 1.1.1

Table 1.1.2 Condition of Rock

Elevation	P4	P5	Type of Rock
EL.L1	926.600	926.600	Water
EL.L2	918.000	921.700	AS
EL.L3	917.000	914.300	weathered BA VS2
EL.L4	913.000	910.600	fresh BA

No	Station	X	Y
A1	15+97.0	1968191.799	27769.074
P1	16+39.5	1968223.229	27797.680
P2	16+82.0	1968254.490	27826.473
P3	17+24.5	1968285.750	27855.265
P4	18+47.0	1968375.855	27938.256
P5	20+67.0	1968537.674	28087.301
P6	21+89.5	1968627.779	28170.292
P7	22+32.0	1968659.039	28199.085
P8	22+74.5	1968690.300	28227.877
A2	23+17.0	1968721.561	28256.670

Future Economic Framework Low Growth Scenario

Zone	Traffic Zone	Prospect of Economic Growth			Prospect of Traffic Growth			Remarks
		Prospect of GNP Increase	Prospect Major Industrial Output	Growth in Cargo Handling at Port	up to 2005	2006-2015	Average	
1	Cape Town		4.20%		4.20%	2.10%	2.80%	
2	East London		4.20%		4.20%	2.10%	2.80%	
3	Durban		4.20%		4.20%	2.10%	2.80%	
4	Northern Cape		4.20%		4.20%	2.10%	2.80%	
5	Johannesburg		4.20%		4.20%	2.10%	2.80%	
6	Swaziland	4.90%			4.90%	2.45%	3.26%	
7	Lesotho	4.50%			4.50%	2.25%	2.99%	
8	Maputo	5.40%		8.50%	5.40%	2.70%	3.59%	
9	Beira	5.40%		10.00%	5.00%	2.50%	3.33%	
10	West Zimbabwe, Bulawayo		4.20%		4.20%	2.10%	2.80%	
11	East Zimbabwe, Harare		4.20%		4.20%	2.10%	2.80%	
12	Zimbabwe, Hwange		4.20%		4.20%	2.10%	2.80%	
13	Western Botswana	6.50%			8.50%	4.25%	5.65%	The rates multiplied 1.3 of elasticity between traffic growth and economic growth
14	Eastern Botswana, Gaborone	6.50%			8.50%	4.25%	5.65%	
15	South Namibia, Walvis Bay, Windhoek	3.40%		12%	6.00%	3.00%	3.99%	Half of Cargo Handling
16	North Namibia	3.40%	4.20%		4.20%	2.10%	2.80%	
17	South Angola		4.20%		4.20%	2.10%	2.80%	
18	Angola, Lobito		4.20%		4.20%	2.10%	2.80%	
19	Malawi	5.00%			5.00%	2.50%	3.33%	
20	Tanzania		4.20%		4.20%	2.10%	2.80%	
21	Congo		4.20%		4.20%	2.10%	2.80%	
22	East Zambia	4.00%			5.50%	2.75%	3.66%	The rates including 1.5% of regional economic development
23	North East Zambia	4.00%			5.50%	2.75%	3.66%	
24	Kabwe	4.00%			5.50%	2.75%	3.66%	
25	Lusaka	4.00%			5.50%	2.75%	3.66%	
26	Copper Belt		15.00%		15.00%	7.50%	9.94%	
27	Western Zambia	4.00%			5.50%	2.75%	3.66%	
28	Kafue	4.00%			5.50%	2.75%	3.66%	
29	Southern Zambia	4.00%			5.50%	2.75%	3.66%	
30	Livingstone	4.00%			5.50%	2.75%	3.66%	

$$\text{Average} = \left[(1+R_1)^5 \times (1+R_2)^{10}\right]^{\frac{1}{15}} - 1$$

R_1 = Traffic Growth Rate (up to 2005)

R_2 = Traffic Growth Rate (2006-2015)

Future Economic Framework High Growth Scenario

Zone	Traffic Zone	Prospect of Economic Growth			Traffic Growth of Low Growth Scenario	Prospect of Traffic Growth			Remarks
		Prospect of GNP Increase	Prospect Major Industrial Output	Growth in Cargo Handling at Port		up to 2005	2006-2015	Average	
1	Cape Town		4.20%			5.50%	2.75%	3.66%	The rates multiplied 1.3 of elasticity between traffic growth and economic growth
2	East London		4.20%			5.50%	2.75%	3.66%	
3	Durban		4.20%			5.50%	2.75%	3.66%	
4	Northern Cape		4.20%			5.50%	2.75%	3.66%	
5	Johannesburg		4.20%			5.50%	2.75%	3.66%	
6	Swaziland	4.90%				6.40%	3.20%	4.26%	
7	Lesotho	4.50%				5.80%	2.90%	3.86%	
8	Maputo	5.40%		8.50%		8.50%	4.25%	5.65%	
9	Beira	5.40%		10.00%		10.00%	5.00%	6.64%	
10	West Zimbabwe, Bulawayo		4.20%			5.50%	2.75%	3.66%	
11	East Zimbabwe, Harare		4.20%			5.50%	2.75%	3.66%	
12	Zimbabwe, Hwange		4.20%			5.50%	2.75%	3.66%	
13	Western Botswana	7.60%				9.88%	4.94%	6.56%	The rates multiplied 1.3 of elasticity between traffic growth and economic growth
14	Eastern Botswana, Gaborone	7.60%				9.88%	4.94%	6.56%	
15	South Namibia, Walvis Bay, Windhoek	4.20%		12.00%		12.00%	6.00%	7.96%	The rates multiplied 1.3 of elasticity between traffic growth and economic growth
16	North Namibia	4.20%				5.50%	2.75%	3.66%	
17	South Angola	4.20%				5.50%	2.75%	3.66%	
18	Angola, Lobito	4.20%		16.70%		16.70%	8.35%	11.06%	
19	Malawi	5.00%				6.50%	3.25%	4.32%	
20	Tanzania	4.20%				5.50%	2.75%	3.66%	
21	Congo	4.20%				5.50%	2.75%	3.66%	
22	East Zambia				5.50%	7.20%	3.60%	4.79%	The rates multiplied 1.3 of elasticity between traffic growth and economic growth and traffic growth of low growth scenario
23	North East Zambia				5.50%	7.20%	3.60%	4.79%	
24	Kabwe				5.50%	7.20%	3.60%	4.79%	
25	Lusaka				5.50%	7.20%	3.60%	4.79%	
26	Copper Belt		30.00%			30.00%	15.00%	19.80%	
27	Western Zambia				5.50%	7.20%	3.60%	4.79%	The rates multiplied 1.3 of elasticity between traffic growth and economic growth and traffic growth of low growth scenario
28	Kafue				5.50%	7.20%	3.60%	4.79%	
29	Southern Zambia				5.50%	7.20%	3.60%	4.79%	
30	Livingstone				5.50%	7.20%	3.60%	4.79%	

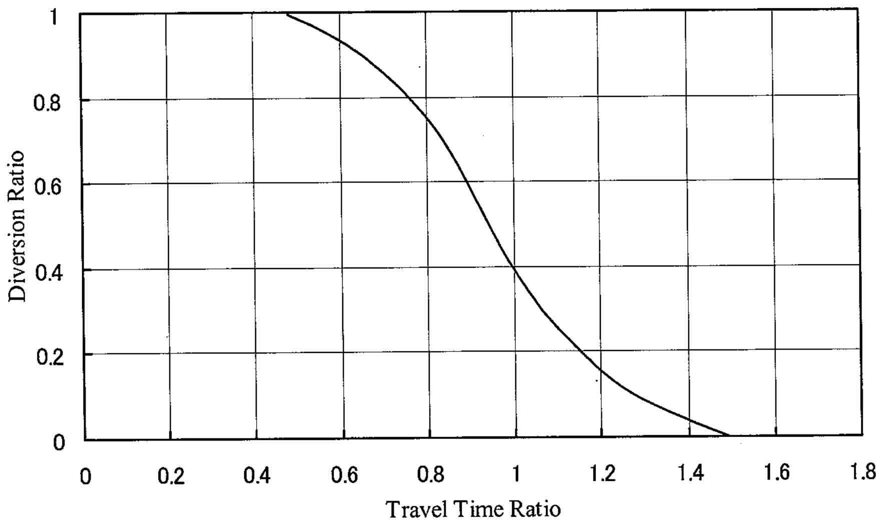
$$\text{Average} = \left[(1+R_1)^5 \times (1+R_2)^{10}\right]^{\frac{1}{15}} - 1$$

R_1 = Traffic Growth Rate (up to 2005)

R_2 = Traffic Growth Rate (2006-2015)

(1) Relation between Route Selection Percentage and Travel Time Ratio

The following traffic diversion curve is used by the Bureau of Public Roads in USA.



Where, traffic diversion is expressed by the following formula:

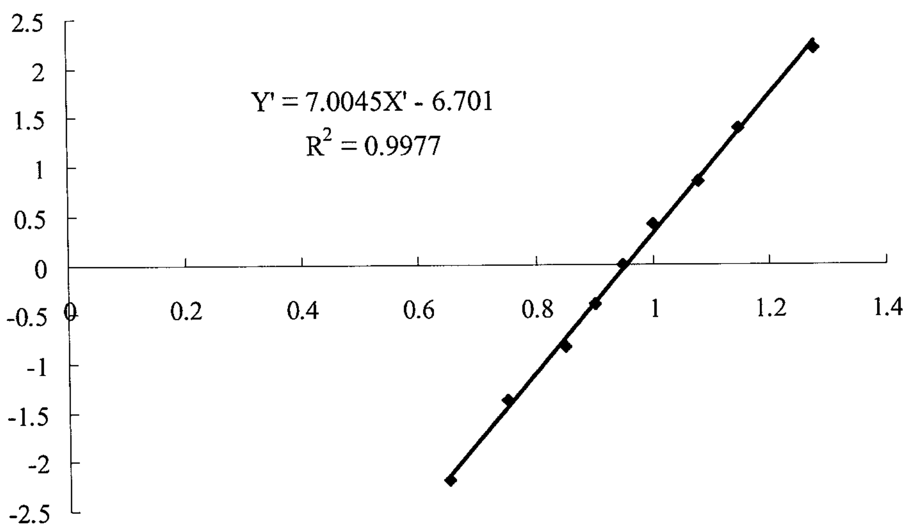
$$y = \frac{1}{1+\alpha e^{-\beta x}}$$

The parameters are obtained by linear regression as follows:

$$\log\left(\frac{1}{y}-1\right) = \log\alpha - \beta x$$

$$Y' = \log\left(\frac{1}{y}-1\right) \qquad \alpha' = \log\alpha - \beta x$$

$$Y' = \alpha' - \beta x$$



Y	X	log((1/y)-1)
0	1.5	
0.1	1.28	2.19722458
0.2	1.15	1.38629436
0.3	1.08	0.84729786
0.4	1	0.40546511
0.5	0.95	0
0.6	0.9	-0.4054651
0.7	0.85	-0.8472979
0.8	0.75	-1.3862944
0.9	0.65	-2.1972246
1	0.48	

then,

$$\beta = -7.0045$$

$$y = \frac{1}{1 + \alpha e^{7.0045x}}$$

where,

y = Percentage of Kazungula Bridge Users

x = Travel Time Ratio (Kazungula Route/Chirundu Route)

The persentage of Kazungula Bridge users is given 0.45, where travel time ratio is given 0.75 with comparison of driving condition between Chirundu route and Kazungula route. The parameter α is given as follows:

$$\alpha = \frac{\left(\frac{1}{y} - 1\right)}{e^{-\beta x}} = \frac{\left(\frac{1}{0.45} - 1\right)}{e^{7.0045 \times 0.75}} = 0.0063896$$

In general, the relation between route selection percentage and travel time ratio is expressed as follows.

$$y = \frac{1}{1 + 0.0063896 e^{7.0045x}}$$

(2) Relation between Toll Rate and Traffic Volume

The relation between Toll Rate and Traffic Volume is also defined by similar diversion formula, where

The share of traffic using Kazungula Bridge is given as follows:

$$y = \frac{V_{kz}}{V_{kz} + V_c + V_{kt}}$$

where,

y = Share of Kazungula Bridge

V_{kz} = Traffic volume of Kazungula bridge

V_c = Traffic volume of Chirundu bridge

V_{kt} = Traffic volume of Katima Mulilo bridge

Traffic cost by way of Kazungula vs average traffic cost by other Zambezi crossing is given by the following formula:

$$x = \frac{{}_{kz}T_c}{\frac{{}_{c}T_c + {}_{kt}T_c}{2}}$$

where,

- x = Traffic cost by way of Kazungula VS Average Traffic cost by other Zambezi crossing
- ${}_{kz}T_c$ = Traffic cost via Kazungula between Lusaka and Durban
- ${}_{c}T_c$ = Traffic cost via Chirundu between Lusaka and Durban
- ${}_{kt}T_c$ = Traffic cost via Katima Mulilo between Lusaka and Durban

On the above assumption, the parameter β, under the same parameter of α, obtained in the (1), is calculated as follows:

$$\beta = \frac{\log\alpha - \log\left(\frac{V_{kz}}{V_{kz} + V_c + V_{kt}} - 1\right)}{\frac{{}_{kz}T_c}{\frac{{}_{c}T_c + {}_{kt}T_c}{2}}}$$

The traffic costs via Kazungula and Chirundu between Lusaka in Zambia and Durban in South Africa are given as follows:

Unit: US$

Route	VOC	Travel Cost	Fee	Total
Kazungula	1,670.9	102.4	29.44	1,802.7
Chirundu	1,516.9	113.1	1.0	1,634.0

As a result, the relation between toll rate and traffic volume is defined as follows:

$$y = \frac{1}{1 + 0.0063896e^{5.0992x}}$$