TOSHKA SPILLWAY BARRAGES STABILITY ANALYSIS

Sherine S. Ismail * and Medhat Aziz **

* Researcher, Nile Research Institute, NWRC, Email: sherine_shawky@hotmail.com.
** Professor, Deputy Director, Nile Research Institute, NWRC, Egypt

ABSTRACT

The High Aswan Dam was constructed during the 1960's. Since then, it has been considered the most important control structure in Egypt controlling a huge volume of water on its upstream (about 162 billion cubic meters). The construction of the High Aswan Dam necessitates providing more safety elements. One of these safety elements is Toshka Spillway which was constructed in 1982 to provide more safety margin for the High Aswan Dam. The spillway is an uncontrolled spillway and the proposed project is to construct spillway barrages to increase Lake Nasser water management efficiency. The purpose of this paper is to introduce a probabilistic model developed to simulate and study safety and stability of Toshka Spillway Barrages. Different possible study cases were considered during this analysis. The resulted exit gradient and uplift distribution, due to the most unfavorable conditions, were produced and evaluated. Normal distribution was used and related statistical distribution fitting tests were applied. The exceeding probabilities of certain safety factors were computed for different cases and the proposed design was accepted. Continuous monitoring is recommended after the barrages construction and the construction of observation wells to monitor barrages safety under different scenarios is a must.

Keyword: Lake Nasser, Toshka Spillway Barrages, Exit gradient, Uplift pressure

HIGH ASWAN DAM

The natural Nile River inflow is characterized by its wide variability during different years. The historical Nile natural inflow data records shown in figure 1 illustrates that the inflow is ranging from a maximum value of 150 billion cubic meters per year (1878-1879) to a minimum value of 42 billion cubic meters per year (1913-1914), Aziz et al [1]. Very low inflows form severe danger of insufficient water recourses for drinking and domestic uses, agricultural water supplies, insufficient hydropower supply, navigation problems due to insufficient water depths and other related problems. On the other hand, very high river inflows represent severe hazard for the river neighborhood communities and endanger hydraulic structures and both river bed and banks. Due to these reasons and others, the High Aswan Dam (HAD) has been constructed in 1960’s. The High Aswan Dam has formed one of the largest man-made lakes all over the world upstream of the dam with a surface area of about 6000 km2 and a volume of water of about 164 billion cubic meters for water level of 182.00. The huge volume of impound water upstream of dam has necessitated to provide enough safety elements for the High Aswan Dam operation and scenarios. On of the basic safety dam safety element is the Toshka Spillway Canal.

TOSHKA SPILLWAY CANAL

Toshka Spillway Canal entrance is located at 285.00 km upstream of the High Aswan Dam to form an additional safety element for the dam. The spillway outflow discharge is governed by the lake water level, the hydraulic and geometrical canal characteristics. The uncontrolled spillway flow causes spillway water discharge, even for low flood years, after exceeding the lake water level of 178.00 reducing the possible water outflow downstream the dam. On the other hand, during high flood years, the spillway water discharge can not be increased to reduce the outflow discharge downstream the dam.

THE PROPOSED PROJECT

The proposed project, Toshka Spillway Barrages, is located 8.00 km from the canal entrance. The main goal of the Barrages is to control the spillway flow during both; low and high flow years. In addition to the Barrages construction, some widening and deepening of the spillway canal are carried out to increase the maximum flow capacity of the spillway canal. Figure 2 shows the Barrages cross section. The Barrages design is shared among different research institutes. Nile Research Institute was responsible for two design stages. The first stage was to outline the proposal operation of the Barrages for different scenarios. The second design stage was to analyze Barrages safety and to propose related safety measures.

Barrages safety factors

Different safety factors were used to indicate the safety and the stability of Barrages elements such as: 1-piping safety, 2-uplift safety, 3-structual safety, and 4-scour-hole Barrages safety. During this analysis, both piping and uplift safeties were studied for Toshka Spillway Barrages due to different flow scenarios.

Developed model

A probabilistic two-dimensional model, developed by the authors, was used to perform the required analysis during this study. The model was based on solving the stochastic equation for the two dimensional steady state:

$$\frac{\partial}{\partial x}\left[K_x \frac{\partial \phi'}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y \frac{\partial \phi'}{\partial y}\right]=0 \qquad (1)$$

where:

K_x is the coefficient of permeability in x direction,
K_y is the coefficient of permeability in y direction,
ϕ' is the hydraulic head.

Spatial variability of the coefficient of permeability

Deterministic analysis for the seepage problems assumes a single value for the coefficient of permeability for each layer. This is a simplified approach and is considered valid for design for small and low hazard structures. The proposed project is considered a high hazard project, one should use more realistic approach by considering the spatial variability of different parameters. The probabilistic approach takes into account the soil properties uncertainty which could be attributed to different factors such as:
1) soil heterogeneity,
2) subsurface information uncertainty, and
3) measurement errors.

The Log-Normal distribution is usually used for simulation of the spatial variability of the coefficient of permeability, Smith & Freeze [2].

Monte Carlo method is used to generate un-correlated coefficients of permeability. The Nearest Neighbor Method was used to generate a multilateral spatial dependence among different coefficient of permeability.

Goodness of fit statistical tests

Statistical tests were performed to judge the applicability of using a certain distribution and to simulate a certain set of data, some of these tests are described as follows:

1- Chi-square goodness of fit test
This test is performed using the following equation, Hann, [3]:

$$\chi_c^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \qquad (2)$$

O Observed value
E Expected value

The parameter χ_c is computed from the previous equation and compared with a standard value determined according the degrees of freedom to determine the significance levels for using a certain distribution.

2- The Kolmogorov-Simirov goodness of fit test

This test is performed by determining the maximum deviation (D):

$$D=\max | P_x(x)- S_n(x)| \quad (3)$$

where

$P_x(x)$ Theoretical cumulative distribution function,

$S_n(x)$ Sample cumulative density function based on n observation.

The computed D parameter is compared with a standard value to determine the significance levels for using a certain distribution, Haan, [3].

3- Visual judgment of data

The visual judgment of data is very essential in determining the used distribution to avoid any inaccuracy in the used statistical tests.

Study Cases

Different cases were considered according to soil bore holes under the barrages footing. Table 1 shows different seven cases for different seven soil logs. The soil bore holes are described in details in Construction Research Institute soil bore holes description, CRI [4]. The simulated water levels are the most unfavorable conditions of 182.00 upstream the dam and footing level downstream the dam. For each case, a repetition of 1000 times was used to simulate the statistical distribution to be as close as possible from the actual statistical distribution.

Table (1) Different study cases

Case	Bore Hole No.*
1	1
2	2
3	3
4	8
5	9
6	14
7	15

* Bore Hole Details are listed in the CRI Report.

MODEL RESULTS

Exit Gradient

Figure 3 shows the developed model exit gradient results for case (1). The exit gradient characteristics for different cases from (1) to (7) are shown in table (2). It has to be mentioned here that the minimum exit gradient ranged from 0.2714 for case (2) and 0.2840 for case (1). While the maximum values ranged from 0.2747 for case (7) to 0.2968 for case (1). The average values ranged from 0.2735 for case (2) to 0.2899 for case (1). The standard deviation ranged from 0.0006 for case (4) to 0.00195 for case (1). The factor of safety against piping was defined as follows, Terzaghi & Peck [5]:

$$F_S = \frac{icr}{iexit} \quad \text{.......} (4)$$

where:

F_s	=	Factor of safety against piping,
i_{cr}	=	Critical gradient, and
i_{exit}	=	Exit gradient at present

From Literature, the factor of safety against piping should has a minimum value ranging from 3-4, Das, [6].
The computed deterministic piping safety factors ranged from 3.45 for case (1) and 3.66 for case (2).

Table (2) Hydraulic exit gradient characteristics for different cases

Case	Minimum	Maximum	Average	Standard Deviation
1	0.2840	0.2968	0.2899	0.00195
2	0.2714	0.2754	0.2735	0.00072
3	0.2811	0.2870	0.2838	0.00088
4	0.2799	0.2804	0.2801	0.00006
5	0.2749	0.2754	0.2751	0.00007
6	0.2785	0.2793	0.2789	0.00012
7	0.2742	0.2747	0.2745	0.00007

Uplift Pressure

Figure 4 shows the uplift pressure results for the case (1). The uplift pressure characteristics for different cases from (1) to (7) are shown in table (3). It has to be mentioned here that the minimum uplift pressure ranged from 37.85 t/m for case (2) and 38.38 t/m for case (1). While the maximum values ranged from 37.98 t/m for case

(2) to 38.56 t/m for case (1). The average values ranged from 37.91 t/m for case (2) to 3.46 for case (1). The standard deviation ranged from 0.013t/m for case (5) to 0.029 t/m for case (1). The uplift forces acting beneath barrage foundation are exerted by the difference in total head above and below the footing level and they tend to uplift a part of or the whole footing. The stabilizing forces for the uplift were represented by weight of the structure foundation and the structure itself if it was applicable. The uplift factor of safety was given by the ratio of the stabilizing forces and the uplift forces. Generally, an uplift factor of safety higher than 1.2-1.3 was considered adequate, Das [6]. The computed deterministic uplift safety factors ranged from 2.85 for case (1) and 2.89 for case (2).

Table (3) Uplift pressure characteristics for different cases. (per meter)

Case	Minimum t/m	Maximum t/m	Average t/m	Standard Deviation t/m
1	38.38	38.56	38.46	0.029
2	37.85	37.98	37.91	0.019
3	37.97	38.10	38.04	0.022
4	38.16	38.24	38.19	0.013
5	37.96	38.05	38.00	0.013
6	38.11	38.19	38.15	0.013
7	37.94	38.02	37.98	0.013

Distribution Fitting Results

Different statistical distributions were tested for both exit gradient and uplift pressure for all seven cases. Normal distribution was selected for this analysis. Figure 5 shows an example of normal distribution fitting for case (1) exit gradient while Figure 6 illustrates an example of normal distribution fitting for case (1) uplift pressure. The following section describes the statistical test results for normal distribution fitting.

Exit Gradient

Table 4 shows the statistical test results for normal distribution fitting for exit gradient. The significance level percentage for Chi-square test for case (1) was 64.28% and it was 52% for Kolmogrov-Simirov test for the same case. Cases (2) and (3) had significance levels of about 73. % and >99% for both tests respectively. From these test results and visual judgment, normal distribution fitting could be accepted for the first three cases. Cases from (4) to (7) had low significance level for normal distribution fitting and this distribution could not be accepted without further studies.

Table (4) Exit gradient statistical test results

Case	Chi Square Test %	Kolmogrov-Simirov Test %
1	64.28	52
2	73.04	>99
3	73.16	>99
4	<1	<1
5	<1	<1
6	<1	<1
7	<1	<1

Uplift pressure

Table 5 shows the statistical test results for normal distribution fitting for uplift pressure. The significance level percentage for Chi-square test for case (1) was 77.72% and it was >99% for Kolmogrov-Simirov test for the same case. Other case results are shown on the mentioned table. From these test results and visual judgment, normal distribution fitting can be accepted for all seven cases.

Table (5) Uplift pressure statistical test results

Case	Chi Square Test %	Kolmogrov-Simirov Test %
1	77.72	>99
2	48.44	>99
3	95	>99
4	76.28	>99
5	63.56	>99
6	92	>99
7	71.24	>99

Safety Factors Exceeding Probabilities

Piping Safety Factor

Table 6 describes the exceeding probabilities for piping factor of safety. From this table, it can be concluded that the exceeding probabilities of piping factor of safety of 3 is 100% for all cases while the exceeding probabilities of piping factor of safety of 4 is 0% for all cases.

Table (6) Exceeding probabilities for piping safety factors

Case	Piping Safety factor Exceeding 3.00 Probability %	Piping Safety factor Exceeding 4.00 Probability %
1	100	0
2	100	0
3	100	0
4	100	0
5	100	0
6	100	0
7	100	0

Uplift safety factor

Table 7 shows the exceeding probabilities for uplift factor of safety. From this table, it can be concluded that the exceeding probabilities of uplift factor of safety of 1.20 is 100% for all cases and the exceeding probabilities of uplift factor of safety of 1.30 is 100% for all cases.

Table (7) Exceeding probabilities for uplift safety factors

Case	Uplift Safety factor Exceeding 1.20 Probability %	Uplift Safety factor Exceeding 1.30 Probability %
1	100	100
2	100	100
3	100	100
4	100	100
5	100	100
6	100	100
7	100	100

Sensitivity Analyses

Sensitivity analyses were performed to study the effect of increasing both cutoff wall and floor lengths on the resulted factor of safety. The results of the performed analyses are shown on the following section.

Cutoff Wall Length

The effect of increasing the cutoff wall length on safety factors was studied during this analysis. The tested length ranged from 6.00 m (the original length) up to 15.00 m. Due to the increase of the cutoff wall length, the piping safety factors were increased slightly. The deterministic analysis showed an increase of piping safety factor from 3.45 to 3.46 due to the increase of cutoff wall from 6.00m to 8.00 m. It also showed an increase of piping safety factor from 3.45 to 3.50 due to the increase of cutoff wall from 6.00m to 15.00 m. The uplift safety factors were increased by the increase of the cutoff wall length. The deterministic analysis showed an increase of uplift safety factor from 2.85 to 2.91 due to the increase of cutoff wall from 6.00m to 8.00 m. It also showed an increase of uplift safety factor from 2.85 to 3.09 due to the increase of cutoff wall from 6.00m to 15.00 m. These results had shown on table 8. It can be concluded that the increase of the cutoff wall length had no major effect on piping safety factors and the uplift safety factors were already in the safe margin and for this reason stability did not benefit much from increasing the cutoff wall length.

Table (8) Safety factors for different cutoff wall lengths

Cutoff wall length (m)	Piping safety factor	Uplift safety factor
6.00	3.45	2.85
8.00	3.46	2.91
15.00	3.50	3.09

Floor Length

The effect of increasing the floor length on safety factors was studied during this analysis. The tested length ranged from the original length up to the increase of the floor length by 5.00 m. Due to the increase of floor length, the piping safety factors were increased noticeably. The deterministic analysis showed an increase of piping safety factor from 3.45 to 3.75 due to the increase of floor length from original length to the original length plus 3.00 m. It also showed an increase of piping safety factor from 3.45 to 3.79 due to the increase of floor length from original length to the original length plus 5.00 m. The uplift safety factors were decreased by the increase of the floor length. The deterministic analysis showed a decrease of uplift safety factor from 2.85 to 2.45 due to the increase of floor length from original length to the original length plus 3.00 m. It also showed a decrease of uplift safety factor from 2.85 to 2.21 due to the increase of floor length from original length to the original length plus 5.00 m. These results are shown on table 9. It can be concluded that the increase of the floor length has some effect on piping safety factors but it has a negative effect on the uplift safety factors.

Table (9) Safety factors for different floor lengths

Floor length	Piping safety factor	Uplift safety factor
Same length	3.45	2.85
Plus 3.00 m	3.75	2.45
Plus 5.00 m	3.79	2.21

Sensitivity Analysis Results

From the previous analysis, it can be concluded that the increase of the cutoff wall length did not have a major positive effect. While the increase of the floor length had a positive effect on the piping safety factor and a negative effect on uplift pressure safety factor. The increase of the floor length requires the increase of floor thickness and these an increase in barrage construction cost. The uplift safety factors were very adequate while the piping safety factors considered accepted and adequate for the following reasons:

1- The down stream water levels occurred only on seasonally pattern, so remedial procedures may be performed every year to prevent the increase of any scour hole.
2- The piping safety factors were computed neglecting the existence of inverted filter layers to increase safety margin.
3- The probability of occurrence of upstream water level of 182.00 m and floor level down stream was very small.

CONCLUSIONS AND RECOMMENDATIONS

The main conclusions and recommendations can be summarized as follows:

1. A two dimensional probabilistic model was developed and used to perform the required analysis and to study safety factors for the proposed Toshka Spillway Barrages Project.
2. A repetition of 1000 times was used to study both exit gradient and uplift pressures.
3. Normal distribution was used to represent both exit gradient and uplift pressures and statistical test results were illustrated.
4. The exceeding probabilities of certain safety factors were computed for different cases.
5. The proposed design was accepted.
6. Continuous monitoring is recommended after the barrages construction.
7. The construction of observation wells to monitor barrages safety under different scenarios is a must.

REFERENCES

1. Aziz, Medhat, Hossam Ibrahim, and Nahla Sadek. Lake Nasser flood and sediment analysis. Proceedings of the Eighth International Symposium on River Sedimentation, (ISRS 8), Cairo Egypt. 2001.

2. Smith, L., and R. Freeze. “Stochastic Analysis of Steady State Groundwater Flow in A Bounded Domain 2-Two-Dimensional Simulations”. Journal of Water Resources Research Vol 15, part 6, pp1543-1559.

3. Haan, C. Statistical methods in hydrology. Iowa State University Press, Ames. Iowa, USA, pp 378, 1986.

4. CRI, Toshka Spillway Barrage soil bore holes. Construction Research Institute, Cairo, Egypt, 2004.

5. Terzaghi, Karl, and Ralph Peck. Soil Mechanics in Engineering Practice”. John Wiley & Sons. New-York. USA, pp 703, 1967.

6. Das, B., “Advanced Soil Mechanics”. McGraw-Hill Book Company, USA, pp 510, 1985.

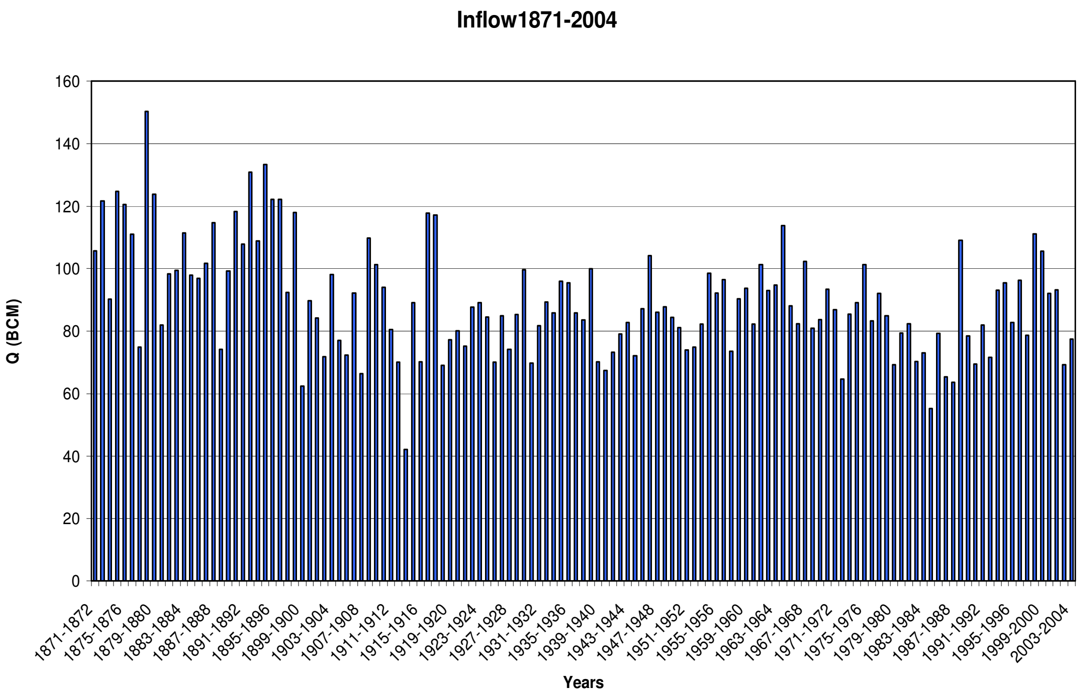

Figure 1. Natural annual Lake Nasser Inflow (BCM)

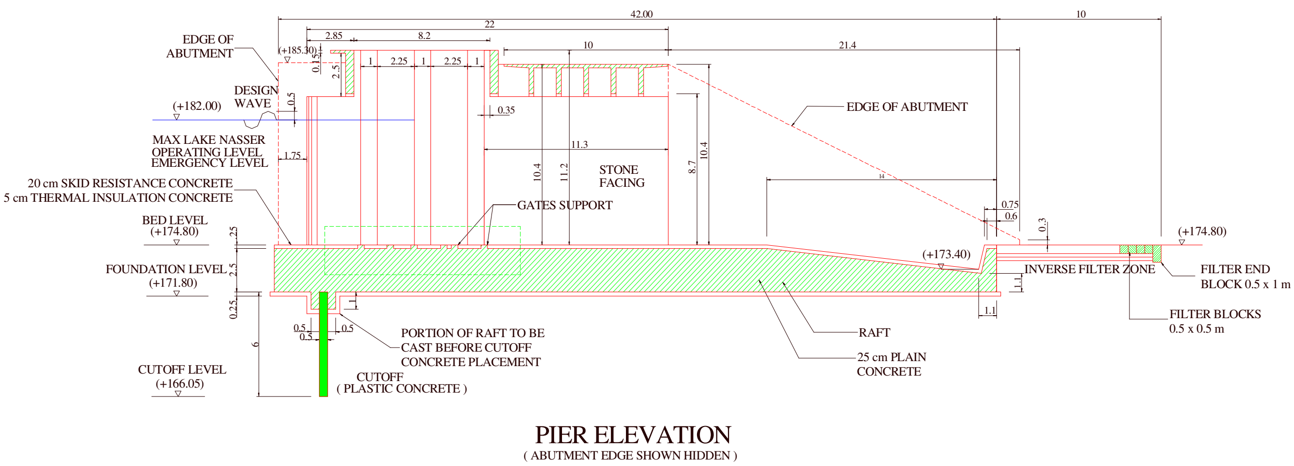

Figure 2. Barrage cross section

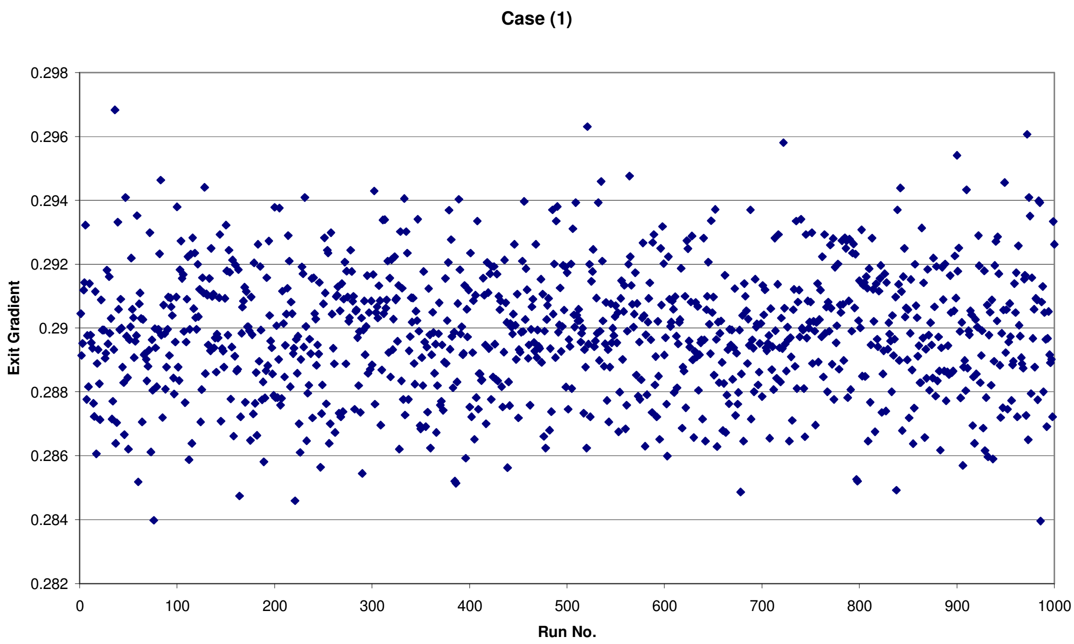

Figure 3. Exit gradient results for case (1)

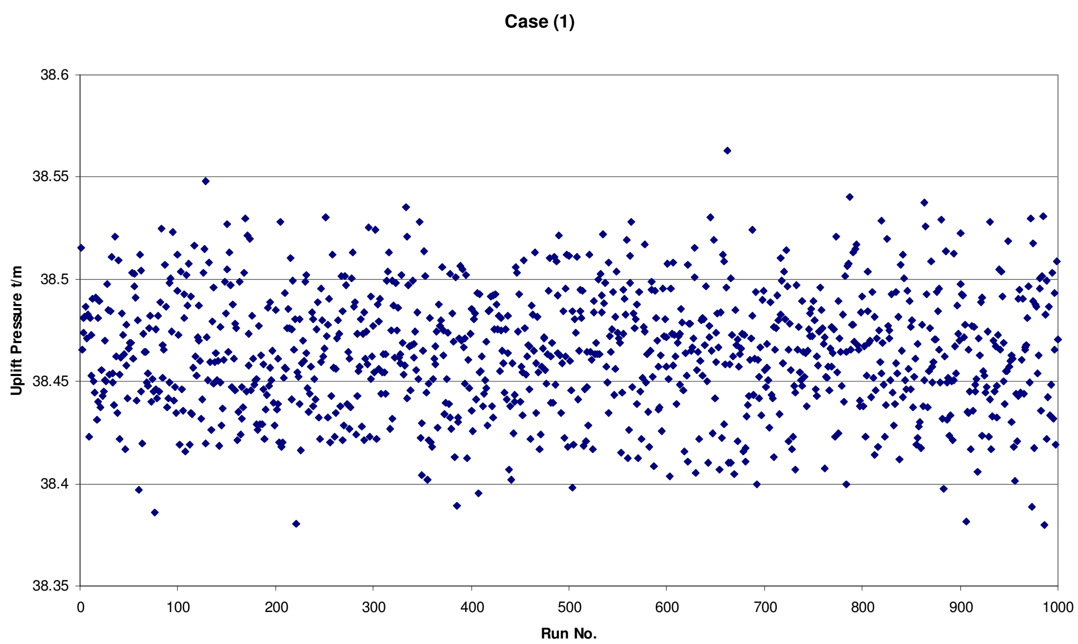

Figure 4. Uplift pressure results for case (1)

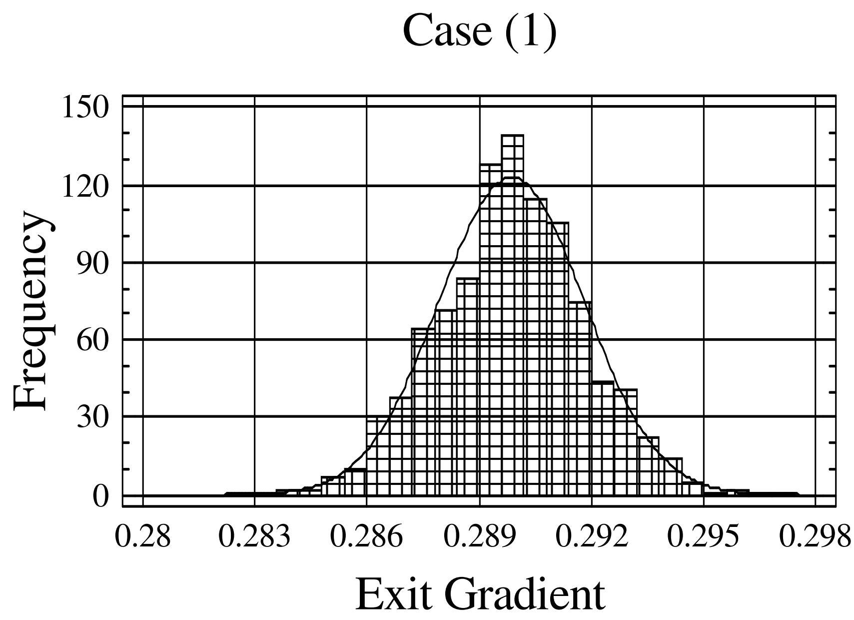

Figure 5. Normal distribution fitting for case (1) exit gradient

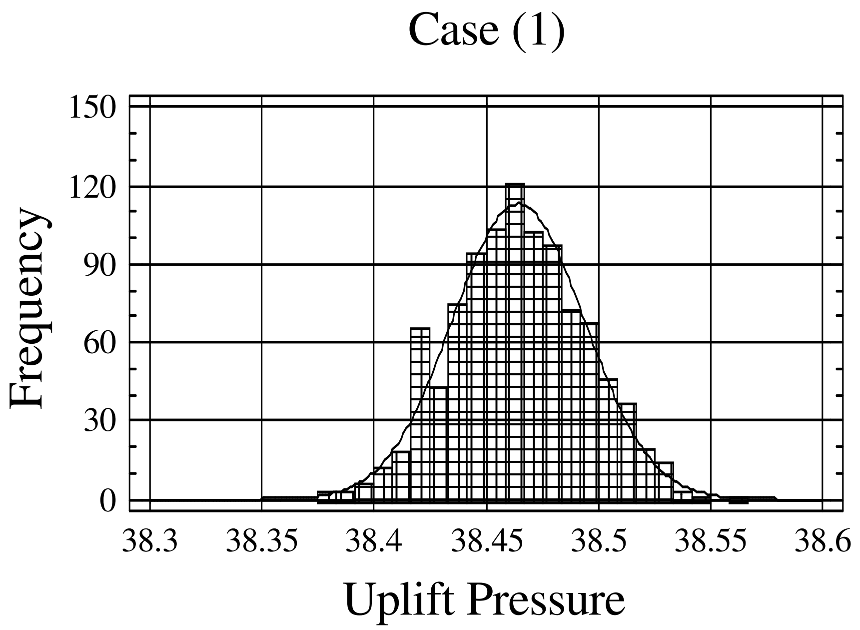

Figure 6. Normal distribution fitting for case (1) uplift pressure