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Our Ref: PSM1059.TL8
Date: 30 January 2007

The Project Manager
Hornsby Quarry Redevelopment
Hornsby Shire Council
PO Box 37
HORNSBY NSW 1630

ATTENTION: MR CRAIG CLENDINNING

Dear Sir

RE: <u>REVIEW OF QUARRY REPORT BY DR CHARLES GERRARD</u>

We refer to the letter from Dr C Gerrard to Council dated 29 January 2007 in which he has reviewed the draft report PSM1059.TR1.

The discussion below centres around the points made in Dr Gerrard's letter under the heading Major Criticisms.

<u>Slope Instability</u>

PSM have chosen to present the results of our stability assessment based on factors of safety (FOS) for potential failure paths/mechanisms. As discussed in the report, we have adopted a target FOS of 1.5 as the minimum value for slopes to be judged as suitable for general public access. This is based on internationally accepted practice (Reference 2). PSM consider that this to be an appropriate measure of slope stability for the purposes of this level of study, i.e. an assessment of costs to allow Council to assess the options for land use. If Council wish to think in terms of probability of failure then it should be noted that a FOS = 1.5 is generally taken as equivalent to be a probability of failure of 1 in 1,000.
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An assessment of the probabilities of failure would allow a risk-benefit analysis to be undertaken. However, the assessment of the site in these terms would not have facilitated a simple and clear discussion of the issues with Council. Indeed, the number of assumptions that may be required for this approach may well mask the true accuracy of the assessment and provide Council with a misleading level of confidence in the stability assessment. In this regard we refer you to the following quote from a paper by Baynes in Reference 1.

"This resulted in assessed probabilities which, whilst being defensible, nevertheless were approximations. Indeed it was stated in the report that different approaches could generate probabilities that might differ from the reported figures by several orders of magnitude, and yet still be based on reasonable considerations. Nevertheless, once the probabilities had been reported they were seized upon and given far greater credibility than was considered justified. This resulted in attention being focused on the values of the assessed probabilities relative to possible acceptance criteria, whilst ignoring the attendant imprecision of the figures and the fact that acceptance criteria had not been established."

We also enclose an extract from a paper by Mostyn and Fell (also in Reference 1) that we think will illustrate two issues, namely:

1. Failure probabilities are not a simple matter, and

2. Council personnel would find it very difficult to follow the technicalities and to appreciate the limitations.

In relation to the quarry itself, the order of magnitude of costs to complete backfilling or other stabilisation works is a significant number. The refinement of these costs that may have been able to be realised through a probabilistic based approach is thought unlikely to be significant compared to the total cost estimates.

In terms of the potential variation with time of slope stability, PSM consider the assessments have taken a reasonable view of scenarios that would have the most significant impacts. The prime factors in this regard are the increase in ground water levels as the quarry lake level rises and the adoption of material strength parameters that are considered appropriate for a long term assessment of the quarry stability.

Finally, we suggest that a probability based approach may be appropriate at a later stage in the process when Council have made an initial selection of uses for some parts of the quarry based not only on geotechnical grounds, but also on the issues of amenity and integration with overall Council policy and development.

- PSM do not propose to alter the report with regard to these issues.

<u>Limits to Development Areas</u>

The location of the boundaries of Part 1 (quarry void) in relation to Parts 2, 3 and 4 (Refer Drawing PSM1059-3) have been made to ensure a FOS of greater than 1.5 is applicable to the ground below these areas regardless of remedial works undertaken at the quarry. In particular, the boundary at the northern sides of the crusher plant area and the south western fill area have been denoted at the boundary between the breccia and the Hawkesbury sandstone.

- We propose to add a paragraph in Section 3.2 of the report to provide further explanation of this point.

In relation to the stability of the lands north or the quarry boundary, Dr Gerrard correctly notes that there is a risk of instability associated with the slopes immediately north of the boundary. The boundary between areas of low risk and moderate and higher risks around the quarry (Refer Drawing PSM1059-18) should be located at the interface between the breccia rock and the Hawkesbury sandstone – i.e. some 15 to 20m north of the property boundary.

- Drawing PSM1059-18 should be modified to denote this and comment made in the report under Section 3.3, (second bullet point).

- The comments above may lead Council to consider restricting new development on the private land immediately north of the quarry. This point should be included in the report in Section 4.2.

- Council may also consider a risk based assessment of the northern slope if the issue of acquisition of all or part of the properties to the north is to be considered. At this stage we propose only to add a comment in the report that this work may be considered in Section 4.2.

There is a minor inconsistency between the text in the second bullet point on page 8 in the main text and the discussion in Appendix E (bullet 2, page 18) regarding the risk to existing houses north of the quarry. The text in the main report (Section 3.3, second bullet point) shall be amended to read:

- There is no *meaningful* risk of deep seated sliding of the northern face of the quarry affecting existing buildings and infrastructure to the north of the quarry. However, there is moderate risk of slips that could impact on the north face within the footprint of Part 1.

Lastly, the issues pertaining to the drilling of boreholes for this project were discussed in our letter PSM1059.TL4 dated 15 November 2006.

Viewing Platform

The discussion on the viewing platform has been misread. The report recommends particular studies be undertaken at any location selected to check for local instability and erosion issues.

Quarry Options and Costing

As we made the point in our presentation to Council in November PSM and in the report, we have not considered each and every option that may be possible for the site. Rather, we have addressed a limited number of options following the initial start up meeting with the Council. This list was expanded slightly following the presentation to Council. We do not propose to assess the “recreational lake” option.

Notwithstanding the discussion above, an option to cut back the quarry walls to (a) provide increased stability for the quarry and (b) provide fill on site to assist with the quarry stabilisation is an option that has merit and should have been canvassed in the report.

We propose to include the following in Appendix E to the report, and with a summary comment in the main text.

- *A balance may be achieved between fill placed in the quarry void and material won through flattening the batters around the quarry excavation. Preliminary calculations show the following:*

    - *Place dumped fill in the quarry to about RL56m – all fill materials sourced from flattening of the existing quarry walls – requires about 1.1 million cubic meters of filling.*

    - *Cut back the northern slope above RL56m to about 1.85 to 1.9(H):1(V).*

    - *Cut back the southern wall to about 1.15(H):1(V) – no impact on Part 3 boundary.*

    - *Flattening of batters at the eastern side are not considered necessary. Major stabilisation works to the eastern and western faces may be able to be limited to minor cut backs to simply provide an improved level of stability.*

    - *Provision of slope drainage measures – horizontal drains.*

    - *Excavation and placement costs (dumped fill) estimated to be $6.55million.*

    These works should be able to be designed to provide an overall FOS of 1.5 or more for the quarry faces. Depending on final geometry and access paths, it may be possible for the quarry to be accessed by the public, or at least a walking path from north to south established.

    A potential limitation on these sort of works would be excavation of the slightly weathered and fresh breccia. It is expected (and costed) these works would involve drill and blast techniques which may pose particular problems with Council and/or nearby residents.

<u>Quarry Backfill</u>

The subsections in Appendix E, E7.2.3 and E7.2.4 should be summarised in the main text to highlight the issues that pertain to a dumped fill versus an engineered (compacted) fill and the prospects for gaining revenue from filling operations.

We propose the following amendments to the report.

- The summary of costs in Section 5 of the main report and Appendix E be modified to denote the fact that it is new fill sourced from areas other than the quarry site. The proposed changes to Section 5 of the report are summarised at the end of this letter.

- Main Text – Section 4.2

    The increase in costs to provide a well compacted, *engineered* fill compared to a dumped fill are considered significant. This must be carefully considered in the light of experiences of projects such as Penrith Lakes and the Enfield Brick pit where approval of apparently well engineered fills for residential uses is very difficult and are thought to be unfeasible due to insurance issues.

Monitoring

PSM consider that the monitoring system discussed in Appendix E of the report is suitable at this time, as discussed in the report. In terms of the report, it would be appropriate to provide a summary discussion about the monitoring in the main text.

- We propose to include summary of monitoring section from Appendix E in the main text of the report.

Revised Section 5 of main report.

5. SUMMARY OF COST ESTIMATES

Quarry Remedial Works

1.	Do Nothing to Quarry	
a.	Maintain lake at RL30m – purchase & install pump and establish 3 phase electricity supply	$20,000
b.	Annual pumping costs	$2000 p.a.
c.	Access to quarry floor For infrequent access/use	$182,000
	TOTAL (50 years)	≈$0.3 million
2.	Backfill Works	

New Fill Purchased for use as a dump quarry backfill

a.	Stabilise entire quarry - remove all instability issues	>$60 million
b.	Stabilise quarry and north batter	>$55 million
c.	Stabilise north batter only	$38 to 43 million
d.	Move fill from Parts 2 and 4 into quarry	$1.85 and 1.5 million respectively
e.	Access to quarry floor For backfilling operations	$304,000
3.	Mechanical Stabilisation	
a.	All quarry faces	$6.5 million

b.	Design, Inspection and Certification		$0.3 million
c.	Drainage works		$0.75 million
d.	Contingency (set at 30%)		$2.3 million Approximately
		TOTAL	$10 million

4. Cut Back Existing Batters and Backfill Quarry

New dumped fill sourced from battering back of existing batters. Fill placed in void to about RL56m in a balanced cut/fill operation.

a.	Fills, residual and highly weathered rock		$1 million
b.	SW/FR breccia – pre spilt with drill and blast		$4.5 million
c.	Access to quarry floor For backfilling operations		$304,000
d.	Drainage works		$0.75 million
		TOTAL	about $6.55 million

5. Monitoring

We would recommend these costs be included with any of the options above from Don nothing to supporting the quarry. Total ongoing costs will depend on the option selected and results found.

Establishment

a.	Establish Survey	$10,000
b.	Establish Rainfall	$250
c.	Establish Lake Level Pole	$1,000
	Total	$11,250

Ongoing Measurements (initial 12 month period)

d.	Ongoing Survey	$15,000
e.	Ongoing Rainfall	$6,500
f.	Ongoing Lake Level	$1,300
g.	Ongoing Face Inspections	$10,000

h.	Ongoing Piezometer	$2,000
	Total	$19,800
	OVERALL TOTAL COSTS	$31,050

Walking Track At North Face

1.	Support Batter below Track	
a.	Compacted Backfill	$300,000
OR		
b.	Rock bolts and shotcrete	$180,000
2.	Stabilise Slopes above track	
a.	Shotcrete and dowels	$55,000
b.	Fill Removal	$278,000
c.	Stormwater Control	$110,000
d.	Outlet pipe erosion control	$15,000
	TOTAL	$458,000
	OVERALL TOTAL	$638,000

Develop Eastern Area (Part 2)

Costs dependant on land use(s) selected.

Develop Crusher Area (Part 3)

1.	Costs are dependant on the land use(s) selected	
2.	Reinforced earth (RE) wall to maximise useable land	$3.15million
3.	Stabilise existing fills (in-situ)	
a.	Flatten batters	$200,000
b.	Soil nails	$2 million
c.	Series of gabion walls	$750,000
d.	Drainage measures for b. and c. above	$150,000

Develop South West Fill Area (Part 4)

1. Costs are dependant on the land use(s) selected

2. Stabilise existing fills (in-situ)

a.	Flatten batters	$100-150,000
b.	Drainage measures	$150,000

Viewing Platform

1.	Eastern Area	$20,000 - $30,000
2.	Western Area	$30,000 - $60,000

For and on behalf of
PELLS SULLIVAN MEYNINK PTY LTD

DEREK ANDERSON

REFERENCES

1. Cruden and Fell (1997) Landslide Risk Assessment.

2. Walker and Fell. Soil Slope Instability and Stabilisation, Balkema 1987.

Landslide Risk Assessment, Cruden & Fell (eds) © 1997 Balkema, Rotterdam, ISBN 90 5410 914 9

Quantitative and semiquantitative estimation of the probability of landsliding

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ABSTRACT: The probability of landsliding can be estimated using quantitative and semiquantitative methods. The paper reviews these methods, their application and limitations.

1 INTRODUCTION

The estimation of the probability of landsliding is one of the critical components of the assessment of landslide risk and hazard for natural and constructed slopes.

The probability of landsliding can be estimated using formal probabilistic analysis approaches which are inherently quantitative in nature, or using semiquantitative methods based on historic records, geomorphology, rainfall, slope geometry and performance and other indications. This paper gives an overview on these methods based largely on the authors' experience, but also referencing examples from elsewhere. The objective is to outline the methods and discuss their applicability and limitations.

2.5 *Factors affecting the probability of failure*

There are several factors that can have a significant impact on the actual value obtained for the probability of failure of a particular problem (Mostyn and Li, 1993). Some of the more important of these are:

- the probability density function assumed for the probability of failure
- the deterministic model adopted as the basis of the probabilistic solution
- effects of various forms of correlation.

These will be discussed in turn.

Probability density function

Many of the methods of evaluating the probability of failure rely on first determining the moments of the distribution of $G(X)$. Even if the mean and standard deviation of $G(X)$ are known, the simple choice between various probability density functions to model *G(X)* can lead to large variations in the estimated probability of failure. Baecher (1987) illustrates this by an example giving the probability of failure for various values of the mean and co-efficient of variation for each of three different probability density functions adopted to model the factor of safety (linearly related to *G(X)*). In the example given a factor of safety with a mean of 2 and a co-efficient of variation of 0.2 (ie. standard deviation of 0.4) the following approximate probabilities of failure were found:

- $2x10^{-3}$ if the factor of safety is assumed to be normally distributed,
- $2x10^{-4}$ if log-normally distributed, and
- $2x10^{-4}$ if gamma distributed.

Thus this "simple" assumption can lead to an order of magnitude variation in the estimate of the probability of failure. It should be noted that generally a symetrical distribution, like the normal, is assumed.

Deterministic model

The choice of the deterministic model can have a significant effect on the estimated probability of failure. Say a slope has been analysed using a Monte Carlo simulation with an extremely high number of simulations; to improve the efficiency of the computation many such simulations are based on the ordinary method of slices. In this case the factor of safety could well have a mean of 1.1 and a standard deviation of 0.2 and be approximately normally distributed; this would result in an estimated probability of failure of about 30%.

But if a slightly more complicated deterministic model was adopted, say Bishop's simplified method, then it is well known that this generally gives slightly higher factors of safety than the ordinary method. Thus it is likely that the mean of the factor of safety may well be higher at, say, 1.3 but the standard deviation and distribution are unlikely to change significantly. In this case the estimated probability of failure would be 7%.

Further it is well known that two dimensional limiting equilibrium methods are conservative when compared with equivalent three dimensional models. Thus if the appropriate 3-D model and adequate computing resources were available, the computed mean factor of safety may well be 1.6 with a standard deviation and distribution similar to the cases discussed above. In this case the estimated probability of failure would be 0.1%. Figure 1 shows these effects.

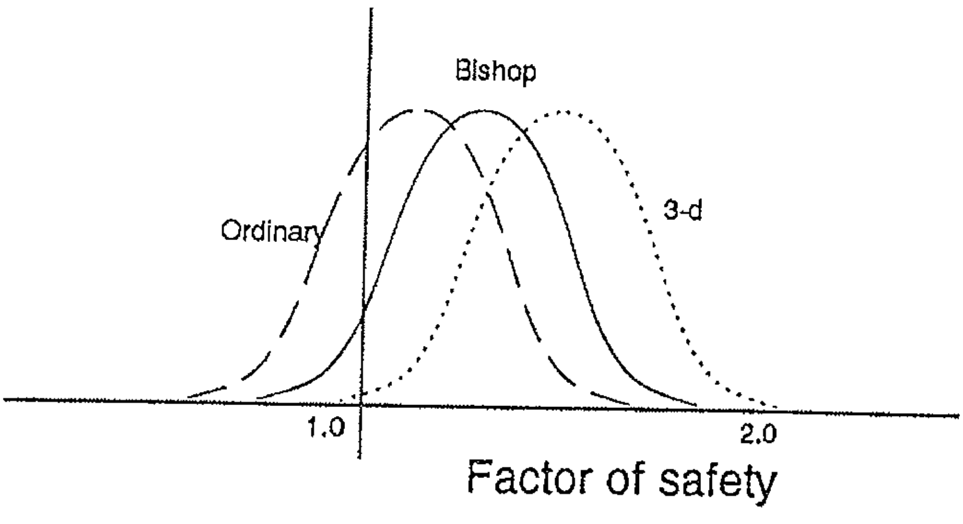

Figure 1. Effect of deterministic model.

Thus a change in deterministic model producing a 30% reduction in the factor of safety has led to a 300% increase in the estimated probability of failure and a 500% increase in the reliability, β. The variation in the factor of safety is not really a problem because the acceptable factor of safety is to a large extent conditioned by the choice of deterministic model but there is not yet the experience to do this with probabilities of failure.

Effects of correlation

Several forms of correlation can effect the probability of failure of a slope; these include:

- correlation between parameters
- correlation between failure surfaces, and
- correlation of a parameter with itself in space.

These are discussed in turn below.

Correlation between strength parameters

Many researchers have based their probabilistic method on the assumption that the shear strength parameters (c and ϕ) are independent (A-Grivas and Asaoka, 1982; Tobutt and Richards, 1979; Chowdhury, 1984; Oboni et al, 1984; Bergado and Anderson, 1983; Vanmarcke, 1980; Alonso, 1976). This assumption is often made to simplify the analysis, many of the writers refer to the paper of Alonso (1976) in support of the assumption, others offer no support.

The evidence offered by Alonso is not strong but does indicate a weak negative correlation for unsaturated residual soils. A-Grivas and Harrop-Williams (1979) state that cohesion and friction are negatively correlated (ie. a high angle of friction is associated with a low cohesion) and provide one example. Indeed it should be expected that for any set of strength data derived for a particular soil, the values of c and ϕ derived therefrom would be negatively correlated. Some writers state that correlation can be ignored because the probability of failure for a negative correlation is higher than it is under the assumption of independence, thus this assumption is conservative (A-Grivas and Asaoka, 1982; Chowdhury, 1984; Bergado and Anderson, 1983; Li and White, 1987(b)); Vanmarcke, 1980). This is supported by the cases analysed by Cherubini et al (1983). Recent work by Yu and Mostyn (1994(b)) has indicated that the degree of conservatism in ignoring this correlation may be several orders of magnitude and thus more than is desirable for such an elaborate method (ie. compared with deterministic methods).

Athanasiou-Grivas and Harr (1979) present one analysis in which the probability of failure is 8.8% when the strength parameters are negatively correlated and is only 4.8% when they are assumed independent. This indicates that the assumption of independence is not always conservative and this assumption needs critical evaluation if this result is correct.

The methods outlined by Young (1985) and Tabba (1984) take correlation between the strength parameters into account. It is also easy to take into account using the approximate method of Li (1992(a)).

Correlation between failure surfaces

The matter of most interest is usually the probability of failure of a slope as a whole (ie. system reliability) rather than the more commonly determined probability of failure of a particular surface. The system failure probability can be greatly influenced by the effects of correlation between various failure surfaces.

Consider a slope face undercut by ten planar joint surfaces. If the probability of failure for a single plane of the slope in Figure 2 is 10% then the overall probability of failure of the slope is also 10% if the probabilities of failure for all the planes are perfectly correlated, ie. if one fails then all of them would fail, if one is stable then all are stable. But if the probability of failure on each plane is independent of the probability of failure of the other planes, then the overall probability of failure is the probability that not all planes are stable (ie. $1 - (1 - 0.1)^{10}$) which equals 65%. This matter is discussed further in Yu and Mostyn (1994(a)).

Thus the probability of failure is greatly influenced by correlation of various modes of failure. This leads naturally to a discussion of the effects of correlation of a parameter with itself in space (ie. spatial correlation or autocorrelation).

Autocorrelation

It is intuitively obvious that many geotechnical properties are spatially autocorrelated. For example, if the cohesion of a certain material at a given location is known to be, say, c_0 then we suspect that the cohesion of the same material at a nearby point is more likely to be close to c_0 rather than to the value of the cohesion at some distant point. In spite of this, most probabilistic models have assumed (generally unstated) that each soil property is perfectly

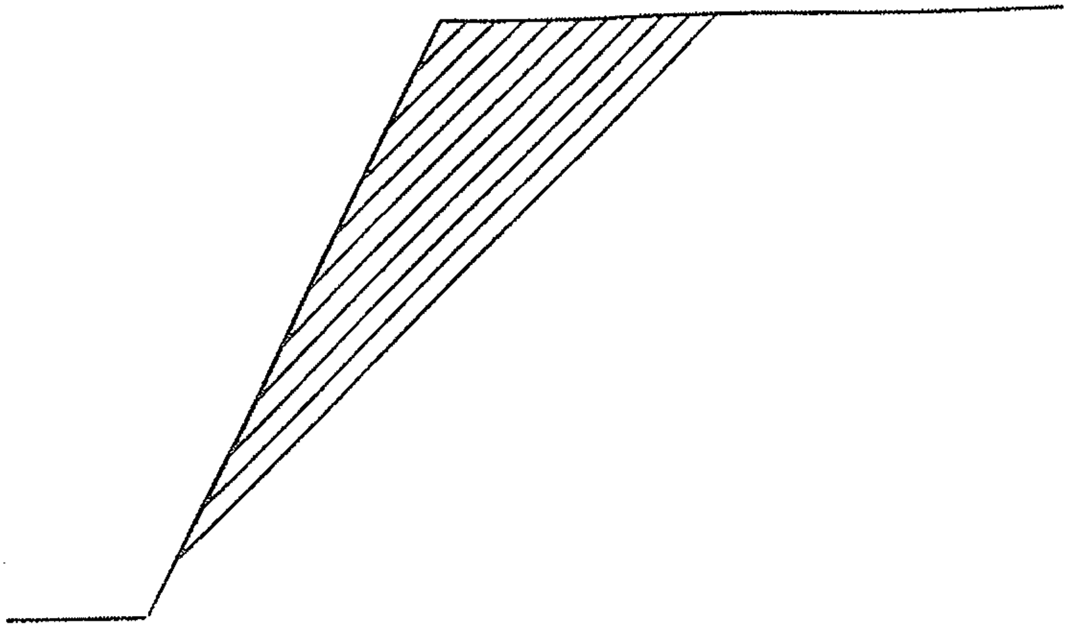

Figure 2. Correlation between failure surfaces.

correlated with itself for an infinite distance. Thus for any given realisation if the cohesion for a soil is say 40 units at one location it is 40 units at all locations. Thus cohesion for the soil is a single random variable which applies uniformly throughout the soil mass. Li and White (1987(c)) comment that ignoring autocorrelation can lead to very large predicted probabilities of failure of, for example, 40% for a factor of safety of 1.2 and that "this kind of scary prediction has no doubt aroused scepticism and an unwillingness to use a probabilistic approach by practising engineers". An example given indicates that the probability of failure may reduce by three orders of magnitude if autocorrelation is taken into account.

Probabilistic models including autocorrelation in 1, 2 or 3 dimensions have been described by many writers. The interested reader should refer to some of the following: Vanmarcke (1977), Christakos (1987), Li and White (1987(b,c)), Schultze (1979), Kulatilake and Varatharajah (1986), Asaoka and A-Grivas (1982), Nguyen and Baafi (1986), Alonso and Krizek (1975) and Bergado and Chang (1986). The work of the first four groups is of most interest and may provide the basis of a suitable practical model. Yu and Mostyn (1993) provide a summary of approaches adopted to modelling rock joints.

To analyse the autocorrelation of geotechnical data generally requires considerably more data than are collected even in a detailed site investigation. Thus analysis is generally based on assumptions regarding the autocorrelation structure of the materials.

Given that autocorrelation exists it is worthwhile to see what effect it has on the results of probabilistic methods of slope analysis. Most methods (ie. most implementations of Monte Carlo, FOSM and PEM) implicitly assume that $\delta_x = \delta_y = \infty$ (ie. perfect spatial correlation), thus a single value of each parameter is taken to apply along the entire failure surface for each realisation.

The effect of this assumption has been illustrated by Mostyn and Soo (1992) who reanalysed several cases from the literature which had previously been analysed assuming perfect (but unrealistic) spatial correlation. They were reanalysed allowing for spatial correlation. One result is shown on Table 1 for a case previously reported by Chowdhury (1987). As can be seen for δ = 10000 (ie. approximating the reported analysis) the probability of failure is 1.9×10^{-2} but analysis allowing for a typical δ_x = 10m and δ_y = 1m results in a reduction in the probability of failure to 2×10^{-5}. Thus ignoring autocorrelation (ie. setting $\delta_x = \infty$) is conservative but the three orders of magnitude conservatism is probably considerably more than desired.

Table 1. Effect of autocorrelation.

δ_x (m)	δ_y (m)	P_f
10000	10000	1.9E-2
100	10	1.3E-E
10	10	6.6E-5
10	1	2.0E-5
1	1	8.4E-6
0.001	0.001	6.0E6