4th International Symposium on Flood Defence:
Managing Flood Risk, Reliability and Vulnerability
Toronto, Ontario, Canada, May 6-8, 2008

Institute for
Catastrophic Loss
Reduction

RISK-BASED DESIGN OF FLOOD DEFENCE SYSTEMS – A PRELIMINARY ANALYSIS FOR THE NEW ORLEANS METROPOLITAN AREA

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ABSTRACT: After the catastrophic flooding of New Orleans due to hurricane Katrina plans are developed for the improvement of the flood protection system of the city. In the article we apply the principles used in the Netherlands for risk based design of flood protection systems to the New Orleans metropolitan area. In this so-called economic optimization the incremental investments in more safety are balanced with the reduction of the risk to find an optimal level of flood protection. In the analysis a flood protection system has been assumed that consists of three different protected areas (or 'bowls'). Based on these layouts it has been investigated how different levels of flood protection affect the investment costs and the residual level of flood risk (= probability of flooding x consequences) and which economic optimum results from this analysis. Although the analyses are preliminary and not yet fully realistic the presented outcomes indicate that for densely populated areas, such as the central parts of New Orleans, it could be justified to choose a higher protection level than the currently proposed level of $1/100yr^{-1}$. The results of the economic optimization can be considered as technical advice that can be used as input for the (political) decision-making.

Key Words: risk assessment, safety standards, optimization, flood defence

1.   INTRODUCTION

"How safe is safe enough?" This question has to be answered in the design of engineering systems. The question is how much safety society desires at which costs, and thus how much risk is tolerated. This is of course a political decision. However, information about the consequences of this decision is often desirable, and risk management techniques may be helpful to provide this information ("risk based informative decision making"). The concept of risk encompasses both the probability of a failure and the consequences of the failure. Risk is generally defined as the product of probability and consequences. The principles of risk analysis are widely used in several engineering fields, for example in nuclear and chemical engineering. The risk concept can be also used for the design of flood defence systems. In this context it is noted that the risk-based principles have been extensively used and explored by the United States Army Corps of Engineers (USACE) in the water management sector (Moser, 2005).

Since the major flood of 1953 the Dutch authorities use risk-based principles in the design, management and maintenance of the flood defences. In this paper we apply the principles used in the Netherlands for risk based design of flood protection systems to the New Orleans metropolitan area. After the catastrophic flooding of New Orleans due to hurricane Katrina plans are developed for the improvement of the flood protection system of the city. In this so-called Louisiana Coastal Protection and Restoration (LACPR) project risk will be an important element and a risk-informed decision framework has been developed (LACPR, 2007). In this paper it is investigated which safety levels result for this area when the so-called economic optimization is applied. The results will give insight in the order of magnitude of the protection level that could be chosen based on such an analysis. The analyses focus on the metropolitan area of New Orleans and will be based on simplified yet realistic information.

Parts of the presented study have been developed as part of the so-called Dutch Perspective (NWP, 2007), a perspective that was prepared for coastal Louisiana by Dutch experts in the field of water and flood risk management. Further backgrounds and details regarding the presented analysis are found in appendix E of the Dutch perspective report.

2. RISK BASED DESIGN OF FLOOD DEFENCE SYSTEMS IN THE NETHERLANDS

Large parts of the Netherlands are below the sea level or the high water levels in rivers and lakes. Without the protection of dikes, dunes and hydraulic structures (e.g. storm surge barriers) large parts of the country would be flooded regularly. The last disastrous flood occurred in 1953 when a storm surge from the North Sea flooded large parts of the Southwest of the country. Apart from immense economic damage, more than 1800 people drowned during this disaster. Until 1953 dikes were constructed to withstand the highest known water level. After the 1953 flood the Delta Committee was installed to investigate the possibilities for a new approach towards flood defence. The committee proposed to reduce the vulnerability by shortening the coastline and closing off the estuaries. In addition, safety standards for flood defences were proposed. In an econometric analysis the optimal safety level was determined for the largest flood prone area, South Holland (van Dantzig, 1956). In this economic optimization the incremental investments in more safety are balanced with the reduction of the risk. The investments consist of the costs to strengthen and raise the dikes. In the simple approach it was assumed that flooding could only occur due to overtopping of the flood defences. Thereby each dike height corresponds to a certain probability of flooding (the higher the dikes the smaller the probability of flooding). Dike heightening leads to reductions of the probability of flooding and the expected damage (= probability x damage). By summing the costs and the expected damage or risk, the total costs are obtained as a function of the safety level. A point can be determined where the total costs are minimal, this is the so-called optimum. The approach has been applied after the 1953 storm surge to determine an optimal safety level was determined for the largest flood prone area, South Holland. In recent work (Eijgenraam, 2006) some modifications of the approach have been proposed.
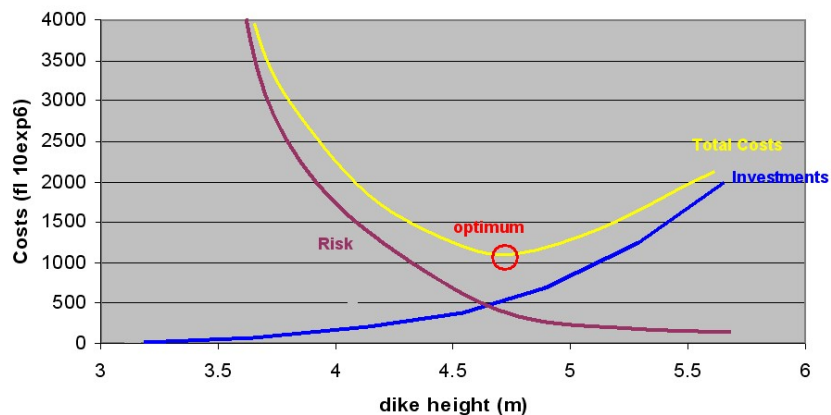

Figure 1: Principle of the Economic optimization approach by the Delta Committee.

The analysis of the Delta Committee laid the foundations for the new safety approach, in which dikes are dimensioned based on a design water level with a certain probability of exceedance. The current design criteria and the process for safety evaluation of the flood defences are based on these design water levels. This approach to flood protection is laid down in the flood protection act of 1996. The flood prone areas in the Netherlands are divided in so-called dike ring areas, i.e. areas protected against floods by a system of water defences (dikes, dunes, hydraulic structures) and high grounds. The safety standards for the various dike depend on the (economic) value of the area and the source of flooding (coast or river). For coastal areas design water levels have been chosen with exceedance frequencies of 1/4000 per year and 1/10,000 per year. For the Dutch river area the safety standards were set at 1/1250 per year and 1/2000 per year. Some smaller dike ring areas bordering the river Meuse in the south of the country have a safety standard of 1/250 per year.

3.   CASE STUDY AREA AND ASSUMPTIONS

3.1   Study area: New Orleans metropolitan area

The focus area in this study is the New Orleans metropolitan area, see figure 3. It is bounded by the wetlands in St. Charles Parish in the West, Lake Pontchartrain in the north, Larke Borgne in the East and the Mississippi river in the south. The area is threatened by flooding from different sources. Hurricanes, high river discharges and heavy rainfall can all lead to flooding. The focus in this investigation is on the protection against hurricane flooding. In the context of the 'Dutch perspective' a (new) flood protection system has been proposed for the New Orleans metropolitan area. It consists of three so-called dike rings or bowls, two Northern dike rings (East bank) and one Southern dike ring (on the west bank), see figure 2. In brief, the works in the two northern dike rings include an upgrade of the existing levees along the Lake Pontchartain (22 miles in the Dikering 1, and 13 miles in Dikering2) and the eastern side of the city (14 miles). In the eastern alignment 19 miles of new levees will be constructed. Floodgates will be constructed in the Inner Harbour Navigation Channel (IHNC) and in the Mississippi River Gulf Outlet (MRGO), see (NWP, 2007; appendix H) for further details.
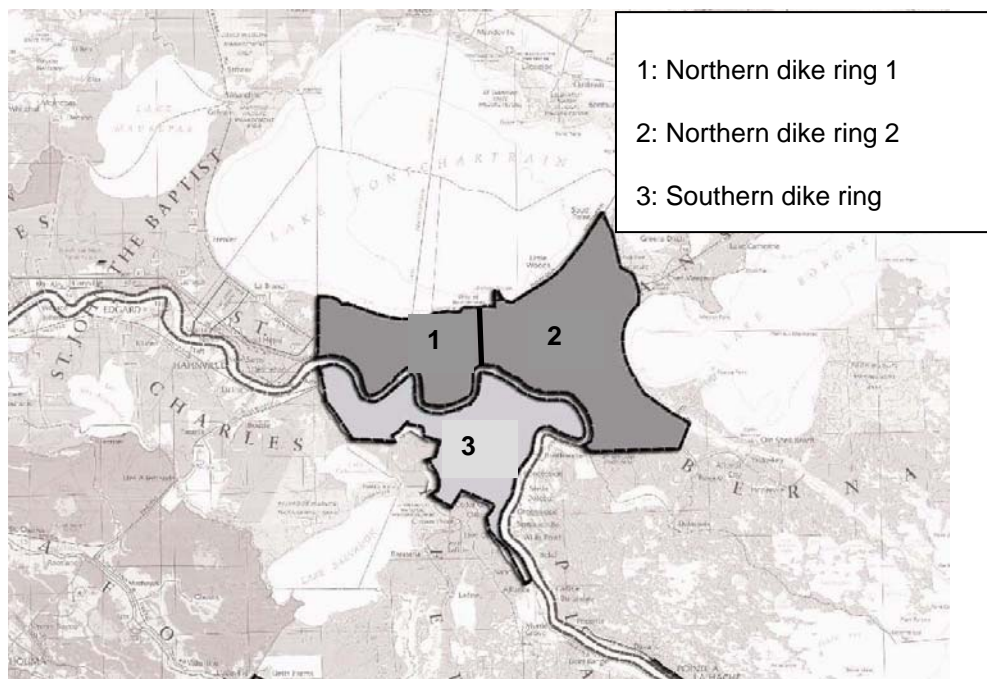

1: Northern dike ring 1

2: Northern dike ring 2

3: Southern dike ring

Figure 2: Overview of New Orleans metropolitan area and proposed flood protection systems in de Dutch perspective.

3.2   Approach, assumptions and input information

3.2.1   Approach

We use the economic optimization approach as described in the previous section. To carry out this approach information is needed for the following elements: 1) The damage due to flooding; 2) The safety level for different system configurations expressed by means of a probability of flooding; 3) The investment costs required for improvement of the system as a function of the safety level. Further below, the assumptions and input information for these points are summarized. Due to limitations in the availability of time and information we use indicative, but realistic estimates for input data for investments costs, flood damage etc.. The presented data are best (but realistic) estimates based on available sources. The sensitivity of the outcomes (i.e. the optimal level of protection) will be investigated for different values of the above-mentioned parameters.

3.2.2   Damage

For the analysis of damage we focus on the potential damage due to hurricane flooding. The considered bowls can flood in different ways due to different hurricane scenarios. The internal topography and the presence of internal boundaries, such as the ridges, could affect or stop the flood flow. For a full analysis different flood scenarios for various hurricane intensities and breaching points would have to be defined. Such an approach would require an in depth and detailed assessment that would not be possible within the constraints of this study. Here a simpler approach is chosen and one 'average' damage value is used for each bowl. It represents the average damage for different possible flood scenarios of the dike ring. Because it is an average damage value it is assumed to be independent of the return period of the hurricane.

In assigning a damage value we use the part of the damage that can be related to the performance of the hurricane protection system. This implies that damage due to failure (breaching) and overtopping of levees will be included. The damage due to rainfall has to be excluded from the analysis as this is related to the drainage and pumping systems. Below the average damage values for the three bowls are shown. These have been determined based on the above assumptions and existing studies related to flood damage (IPET, 2007; Kok et al., 2006). We use the following figures: 1) Northern dikering: central New Orleans: US $ 15 billion; 2) Northern dikering: East New Orleans: US $ 10 billion; 3) Southern dikering: US $ 5 billion.

In the economic optimization the Present Value of the yearly expected damage is calculated. An infinite time horizon is used, and a real discount rate of 2% is assumed (i.e. the long term interest rate minus inflation).

3.2.3   Safety levels

For the analysis of the safety of different system configurations we use the concept of the design water level. It is assumed that the system is designed to safely (i.e. without failure) withstand water levels below the design water level. Water levels exceeding the design water level will lead to severe overtopping and consequent failure of the flood defence system. For the hydraulic conditions a probability of exceedance (per year) can be derived. This implies that the probability of failure of the flood defence system is assumed to equal the probability of exceedance of its design water level. It is noted that for a full probabilistic approach the joint probability of both water levels and waves has to be considered in combination with the possibility of breaching of flood defences for different hydraulic conditions. The following assumptions have been used:

- In analyzing the safety level we take the pre-Katrina situation as a starting point. We estimate that the pre-Katrina safety level was $1/50 \text{ yr}^{-1}$.

- The construction works after Katrina can be seen as a first improvement of the system reliability to approximately a level of 1/100 per year. It is thus investigated in this analysis whether further improvement is justified (see below).

- We investigate the order of magnitude of the optimal protection level by considering various predefined safety levels: 1/100, 1/500, 1/1000, 1/5000, 1/10.000, 1/100.000 yr^{-1}

- The relationship between return period and storm surge level is based on results of IPET, see figure 3 for an example for Lake Pontchartrain. From such figures the increase in the surge level can be estimated that corresponds to a reduction of the return period by a factor 10. For example, from figure 3 it can be seen that a reduction of the return period from 100 to 1000 year corresponds to an increase of the surge level by 3 to 4 feet. Based on the available data we assume a linear relationship between the natural logarithm of the return period and the surge level for return periods larger than 100 years. Similar figures have been used to calculate the increase in water levels for other areas, such as Lake Borgne.

- In the determination of design water level conservative assumptions have been made with respect to the effects of wetlands / marshes. Because it is assumed that the project investment is done for a long time span (at least 100 years) possible deterioration of wetlands in this period is accounted for. This implies that the design water levels are based on a situation in the future with a reduced area of wetlands around New Orleans. The presence of wetlands could reduce the surge and there design water levels and lower the line from figure 3. In future analysis the presence of wetlands could be included.
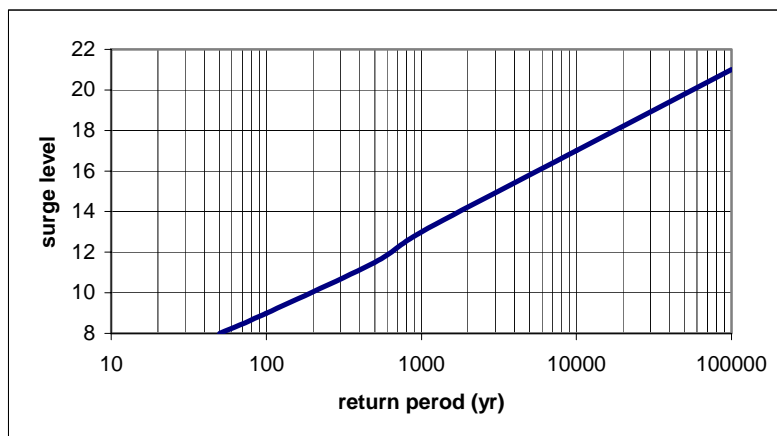

Figure 3: Lake Pontchartrain: relationship between return period and surge level (source: data from IPET)

3.2.4   Investment costs in the flood defence system:

We analyse the required investments in the flood defence system. It is investigated how much investments are required to make a safe system for water levels below the design (water) level. The physical measures in the base case consider dike strengthening and the creation of storm surge barriers. The effects of other measures (e.g. damage reduction and wetlands) can be considered in the same conceptual manner. In the base case optimization these effects are not treated here in detail.

- The investments costs include the costs of additional costs of management and maintenance.

- The investment costs made in the context of Taskforce Hope have been included in the cost estimates.

- The cost estimates have been made based on the length of the levees that have to be upgraded or constructed and unit prices per km of levee strengthening or construction, see Appendix G of the Dutch perspective report.

- The costs of floodgates in the Inner Harbor Navigation Channel and MRGO have been assumed as fixed costs. It is thereby assumed that they are constructed in such a robust way that they are functioning well for different safety levels.

- Overall, the cost estimates are first order and indicative. For a realistic calculation of investment costs more detailed designs have to be used. To account for variations and deviations in the cost estimates the investment costs have been included in the sensitivity analysis.

4. RESULTS OF THE ECONOMIC OPTIMIZATION

4.1 Results for central part of New Orleans

The current yearly risk of this dike ring is equal to US $ 300 million (= $ 15 billion x 1/50). This value can be converted to a present value by dividing by the "net" discount rate (0,02), leading to a present value of US $ 15 billion. If the safety level is improved to 1/100 per year, the present value of the yearly risk will decrease with US $ 7,5 billion, and if the safety level is lowered to 1/1000 per year, the present value of the risk will decrease with US $ 14 billion. This decrease in present value can be considered as the benefits of the project. The results show that the choice of a protection level higher than 1/100 per year, such as 1/500 or 1/1000 per year would already lead to a very significant reduction of the risk level. However, in a cost benefit analysis also the cost of the improvements in safety is important. The results for the base case are presented in table 1 and figure 4. The optimal level of flood protection that follows from the analysis is 1/5.000 years (indicated in bold in the table). Figure 4 shows the following. In terms of total costs there is not much difference with a 1/1000 or 1/100,000 per year protection level. The additional investment costs to reach a 1/10.000 per year level of protection (US $ 200 million) or a 100.000 per year level (US $ 700 million) are relatively limited. For protection levels of 1/100,000 per year and higher the contribution of the risk costs to the total costs becomes negligible.

Table 1: Economic optimization for Northern dike ring, central part of Orleans: Input information and results

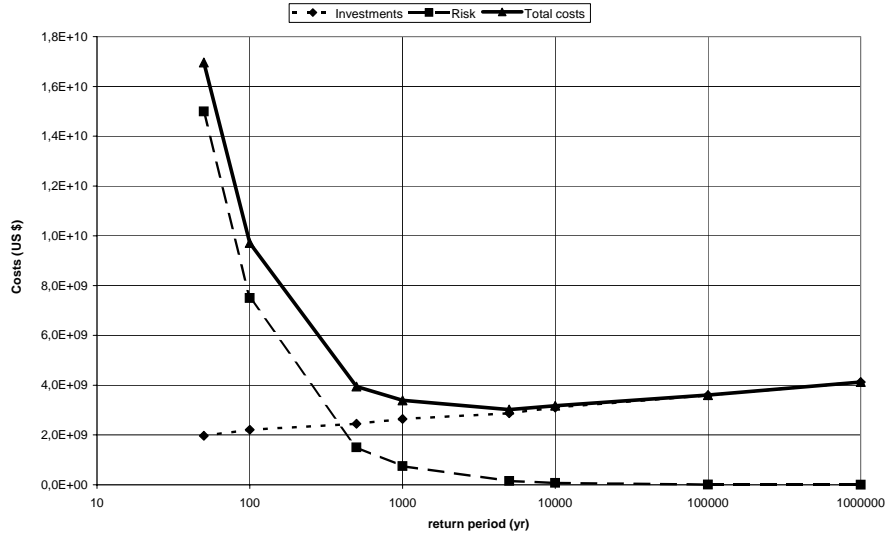| Return period (yr)	100	500	1.000	**5.000**	10.000	100.000	1.000.000
Design surge level Lake Pontchartrain (ft)	9	11	13	**15**	17	21	25
Investments ($)	2,2E+09	2,4E+09	2,6E+09	2,9E+09	3,1E+09	3,6E+09	4,1E+09

Figure 4: Results of economic optimization for the Northern dike ring, central part of New Orleans

The results for the other two bowls (New Orleans East, Southern bowl) are shown in figure 5. For both the areas the optimal level of protection that is found corresponds to a return period of 1/1000 per year.
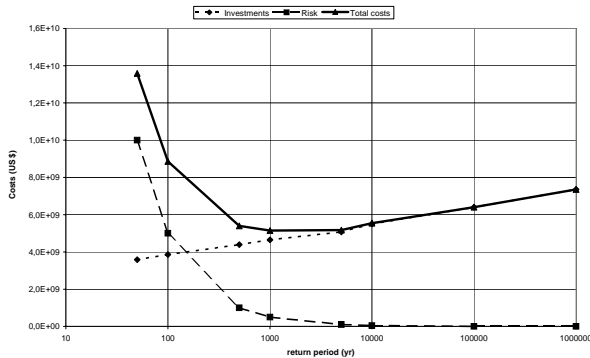
New Orleans east   Southern dike ring
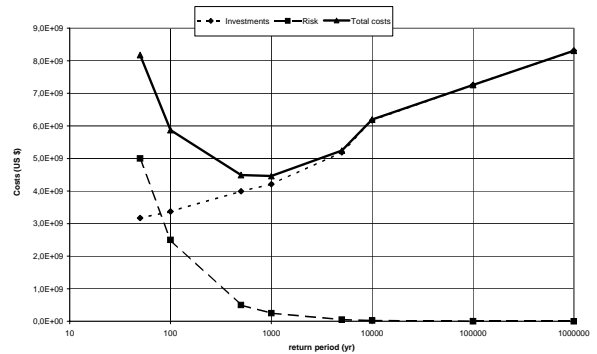

Figure 5: Results of economic optimization for the New Orleans East and the southern dike ring

4.2   Sensitivity analyses

As the estimates that have been used in this study are first-order and rough estimates a sensitivity analysis has been carried out. The sensitivity of the outcomes of the calculated optimal safety level has been investigated for variations in the following parameters: The flood damage value, the value of the real discount rate and the investment costs. Table 2 summarizes the results for the central part of New Orleans. This outcome is not very sensitive for changes in damage level and the investment costs. Only when lower damages are assumed the optimum level of protection reduces to 1/1000 per year

Table 2: Results of sensitivity analysis for the New Orleans metro bowl

	Base Case	Flood damage		Net discount rate		Investment costs	
		50% lower	100% higher	50% lower	100% higher	50% lower	100% higher
Optimal Safety level	1/5000	1/1000	1/5000	1/5000	1/5000	1/5000	1/5000

5. CONCLUDING REMARKS

In this paper we presented the results of a preliminary economic optimization for the safety level of New Orleans. We have use indicative, but realistic estimates for input data. The following has been found:

- Although preliminary and not yet fully realistic the presented outcomes indicate that it is possible to determine the optimal level of safety for the different protected areas in South East Louisiana.

- The results indicate that for densely populated areas, such as the central part of New Orleans it could be justified to choose a higher protection level than the current level of 1/100yr^{-1}. Although the investment costs will be high (billions of dollars), a very large damage can be prevented. The investments are expected to be cost-effective.

- The optimal protection level for the central part of New Orleans is estimated to be in the order of magnitude of 1/5000 per year. This outcome is not very sensitive for changes in damage level and investment costs. The optimal level of protection for New Orleans East dike ring and the Southern dike ring are 1/1000 per year. The following has to be noted: comparison with more recent cost estimates shows that the cost estimates used in this paper are likely somewhat underestimated. Taking into account more realistic (and higher) cost estimates could lead to somewhat lower optimal protection levels. Nevertheless, based on these results and sensitivity analyses it is expected that safety levels that are higher than the 100 year level of protection are always defendable. For example, for the New Orleans metro bowl the choice of a protection level in the range of 500 to 1000 year level of protection would already lead to a very significant reduction of the risk.

- The outcomes also show that a differentiation in protection levels between areas could be justified based on the economic optimization. Such a differentiation in protection levels between areas also exists for dike rings in the Netherlands.

As said, a first order economic optimization has been performed for New Orleans. To obtain better results further investigation of the several factors could improve the results. These include better estimates of damage, investments costs and design water levels. Also, more detailed estimates of the reliability of the system and the remaining risk level would have to be included in the analysis. In addition, the effects of alternative levee system configurations (including storm surge barriers) and the effects of wetlands and multiple line of defence systems could be taken into account. In a more complete optimization also the effects of river flooding from the Mississippi river and rainfall could be taken into account. Although these phenomena are independent from hurricane flooding, they might contribute to the overall flood risk level. In that case also expenditures for the reduction of the risk due to river and rainfall flooding have to be considered. One other aspect that is important in the decision-making is the risk to life. Separate risk criteria could be developed (e.g. risk limits in a so-called FN curve) to set acceptable risk levels in terms of fatalities and acceptable flooding probability (Vrijling *et al.*, 1998; Jonkman, 2007). Finally, the results of the economic optimization can be considered as a technical advice to the decision makers. The decision regarding an acceptable safety level is a political choice, which includes more aspects than economics. A discussion on safety levels and the corresponding decision criteria with involvement of the relevant decision makers and stakeholders could support this broader decision process.

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