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Study on Earthquake Disaster Resilience Evaluation Method of Graded Highway Sections

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Abstract. Graded highway is an important object of regional toughness evaluation. It is necessary to evaluate the toughness of graded highway sections in disaster areas after earthquake disasters, so as to formulate the best emergency rescue plan. There are many aspects of the impact of earthquake disasters on the toughness of graded highway sections. This paper further analyzes the factors of the impact of earthquake disasters on the capacity of graded highway sections, and concludes the disaster factors of the impact of earthquake on the toughness of graded highway sections. The disaster factors of decreasing capacity of grade highway sections caused by earthquake mainly include: underground void, landslide, collapse, debris flow, ground crack, ground subsidence, ground collapse, surface foreign. These disaster factors are important aspects of earthquake disaster resilience evaluation of graded highway sections. Single consistent disaster factors can be combined with their own characteristics to establish the corresponding evaluation criteria. In this paper, the single consistent disaster factors can be graded and evaluated. According to the traffic capacity of graded highway sections, they can be classified into three categories: smooth passage, slow passage and difficult passage. The evaluation index of each level is consistent with that of the single consistent disaster factor. In the process of grade highway section toughness evaluation, the number of lanes is an important index affecting the toughness of the section. The weight coefficient can be used to evaluate the seismic toughness of grade highway according to the number of lanes of the grade highway. The research results of this paper are of great significance to the formulation of a dredging plan in emergency rescue after the earthquake.

Keywords. Graded highways, earthquakes, toughness, evaluation methods

1. Introduction

Since the construction of expressways began in the 1980s, the scale of national expressways has developed rapidly, and the length of expressways has increased year by year. By the end of 2021, the total length of national expressways has reached 161,200 kilometers, and a huge road transportation infrastructure system has been built, which is among the highest in the world [1]. At present, road design and construction mainly focus on traffic volume, load, line type, natural conditions and other factors, and pay little attention to the toughness evaluation of road sections. As an important connecting channel between cities, graded highways should not only meet the daily traffic tasks, but

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also assume the important responsibility of disaster relief in the face of natural disasters. In the face of extreme natural disasters, the toughness of roads can reflect the important value and timely ensure the transportation of vehicles, personnel and materials [2]. The improvement of graded highway toughness cannot be separated from the proposal and optimization of the toughness evaluation method. Currently, the evaluation grade of a single natural disaster has been established, but the evaluation method is targeted at the natural disaster itself and lacks the evaluation grade of the impact of the natural disaster on road sections. Therefore, the toughness evaluation method for the comprehensive graded highway sections of various disaster types needs to be further studied [3].

Graded highway refers to the highway whose technical conditions and facilities meet national or ministerial standards. Highway classification is based on the use of the task, function and flow rate of the highway, the Chinese mainland has divided highways into five levels: expressway, first-class highway, second-class highway, third-class highway and fourth-class highway. For a region, grade highway is an important ground transportation infrastructure in and out of the region, and plays a key role in daily economic life. When facing natural disasters, the patency of graded highway is the guarantee of people's life and property safety [4].

Earthquake, also known as ground motion and ground vibration, is a natural phenomenon caused by the rapid release of energy in the earth's crust, during which seismic waves are generated. The main cause of earthquakes is the collision between plates on the earth, which causes the dislocation and rupture along and within plates. Earthquakes often cause serious casualties, can cause fire, flood, toxic gas leakage, bacteria and radioactive material diffusion, and may also cause tsunami, landslide, collapse, ground cracks and other secondary disasters. According to incomplete statistics, in 2021, a total of 20 earthquakes of magnitude 5.0 or above occurred on the Chinese mainland, causing direct economic losses of 10.7 billion yuan [5].

The massive highway infrastructure is an important component and support of the modern comprehensive transportation system, and its functions need not only secure and reliable service performance, but also resilience against natural disasters and emergencies [6]. However, under the action of natural disasters, the structural safety, flexible operation and disaster resilience of highway infrastructure and its network system are insufficient, and it is difficult to meet the demand for efficient and safe transportation in the construction of a powerful transportation country [7]. Especially in the damage caused by earthquake disasters, graded highways will have landslides, collapses, debris flows, ground cracks, collapses, surface foreign bodies and other damages that affect the traffic capacity of grade-level highways due to earthquake disasters. These damages can be defined as different disaster causing factors according to their characteristics and emergency disposal methods.

Road toughness refers to the ability of a road section to accept disaster damage after an earthquake [8]. When the road section suffers from earthquake disaster, there will be a variety of damage affecting the traffic capacity, and these different damage forms jointly affect the repair time for the road section [9]. The toughness evaluation of the road section can evaluate the difficulty and time of recovery of the road section according to the influence degree of different disaster-causing factors, so as to provide a rescue basis for the emergency personnel after the earthquake [10].

To sum up, this study studied the toughness evaluation methods of graded highway sections in earthquake disasters, analyzed the toughness evaluation methods of road sections by different disaster-causing factors, further calculated and studied the toughness comprehensive evaluation methods of various disaster-causing factors, and finally evaluated the toughness of graded highways in earthquake disasters according to the number of lanes on graded highways.

2. Single Consistent Disaster Factor Evaluation Method

2.1. Underground Void

The discontinuity of cement concrete pavement is what we usually refer to as void. If not treated in time, it will cause broken angles and broken plates, etc., which will affect the service life of the road [11]. Structural discontinuity disease of semi-rigid asphalt pavement refers to the discontinuous contact phenomenon of the structural layer of semi-rigid asphalt pavement caused by uneven settlement of subgrade, subgrade soil consolidation, temperature, humidity, load, material and other factors [12]. The road bearing capacity may decline at the location of such a disease. If it is not treated in time, the road surface will appear pulp, cracking and other diseases, and reflection cracks may also occur on the white-to-black road surface due to the instability of the slab [13].

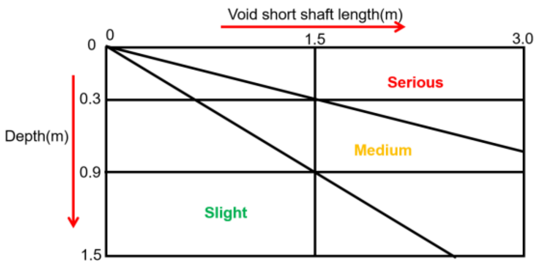


Figure 1. Underground void evaluation method.

underground void is a kind of underground graded highway disaster and one of the disaster factors caused by earthquakes on graded highways. Its evaluation method is shown in Figure 1, which is mainly evaluated by two indexes: length of the short shaft of unloading and occurrence depth [14]. The short-axis length index is used to evaluate the area affected by the release, and the depth of the release is used to evaluate the depth of the release. The larger the area of the release, the heavier the impact will be, and the closer the location of the release to the ground, the heavier the risk and degree of collapse [15]. It is the best method to evaluate the degree of emptying to use the short axis length and the depth of emptying when facing a single consistent disaster factor.

2.2. Landslide, Collapse, Debris Flow

Landslide is a sliding geological phenomenon of rock and soil mass on a slope along the shear failure plane of inertial passage. The mechanism of a landslide is that the shear stress of a sliding plane exceeds the shear strength of the plane [16]. A mudslide is a special torrent of mud and rock that is caused by heavy rain, heavy snow or other natural disasters in mountainous areas or other areas with steep terrain. Collapse is a geological phenomenon in which the rock and soil mass on a steep slope suddenly breaks away from its parent body under the action of gravity and collapses, rolls and accumulates at the foot of the slope. The three kinds of disasters can all be caused by earthquakes and are the earthquake disaster factors of graded highway sections.

In order to better understand and treat the landslide, collapse and debris flow, it is necessary to classify the landslide, collapse and debris flow. However, due to the complex geological conditions and factors in nature, the purposes and requirements of various engineering classifications are not the same. The main classification evaluation methods include: evaluation by volume, evaluation by sliding velocity and evaluation by geological structure relationship of material composition, among which the evaluation by volume is the most appropriate for the toughness evaluation of graded highway. The classification evaluation methods of landslide, collapse and debris flow are shown in Table 1.

Table 1. Standards for classification of the scale of landslide, collapse and debris flow.

Grade	Landslide ($10^4 m^3$)	Collapse ($10^4 m^3$)	Debris flow ($10^4 m^3$)
Giant	≥1000	≥100	≥50
Large	100-1000	10-100	20-50
Medium	10-100	1-10	2-20
Small	<10	<1	<2

When a graded highway suffers from landslide, collapse and debris flow disaster, its recovery time is closely related to the influence area and the volume of the landslide body. The volume index of graded highway toughness evaluation is the best index of disaster evaluation in the case of a single landslide disaster.

2.3. Ground Fractures

Ground crack is a geological phenomenon in which surface rock and soil are cracked under the action of natural or human factors, and cracks of a certain length and width are formed on the ground [17]. When this phenomenon occurs in areas with human activities, it can become a geological disaster. The formation of ground cracks refers to the displacement or misalignment of rock strata due to the misalignment of underground faults during strong earthquakes, and the formation of faults on the ground. Their strike is consistent with the underground fault zone, with large scale and often zonal distribution, they are one of the disaster factors of graded highway caused by earthquakes. The evaluation methods of ground cracks are shown in Table 2.

Table 2. Ground fracture evaluation method.

Scale type*	Giant	Large	Medium	Small
Cumulative length L (m)	L≥10000	10000>L≥1000	1000>L≥100	L<100
Area of influence S (km^2)	S≥10	10>S≥5	5>S≥1	S<1

Note: * indicates that if the evaluation grades of “cumulative length” and “area of influence” are inconsistent, the higher grade shall prevail.

Ground fissures are an important aspect affecting the toughness of graded highways. Its two main evaluation indexes are cumulative length and influence area, which can clearly define the scope and influence degree of disasters. When ground fissures occur on graded highways, they should be supplemented according to the local natural environment. The cumulative length and influence area of a single ground crack disaster are the best indexes for graded highway toughness evaluation.

2.4. Land Subsidence

Land subsidence refers to the subsidence of the ground. It is a major engineering geological problem in major cities of the world. It is generally manifested as regional subsidence and local subsidence. Land subsidence is the ground elevation loss caused by natural factors and human factors [18]. Natural factors include tectonic subsidence, earthquake, volcanic activity, climate change, ground stress change and soil natural consolidation, etc., which is one of the earthquake disaster factors of graded highway. The evaluation method of land subsidence is shown in Table 3.

Table 3. Evaluation method of land subsidence.

Scale type*	Giant	Large	Medium	Small
Accumulated settlement h (m)	h≥1.0	1.0>h≥0.5	0.5>h≥0.1	h<0.1
Settlement area S (km^2)	S≥500	500>S≥100	100>S≥10	S<10

Note: * indicates that if the evaluation grades of “Accumulated settlement” and “Settlement area” are inconsistent, the higher grade shall prevail.

The evaluation method of land subsidence disaster is determined by two indexes: cumulative settlement amount and settlement area, which can clearly define the scope and influence degree of land subsidence disaster respectively. The cumulative length and influence area of graded highway toughness evaluation are the best indexes for disaster evaluation when the land subsidence disaster is single.

2.5. Ground Collapse

Ground collapse refers to the failure of overlying strata. The rock and soil mass sinks or collapses in the underground cavity, and forms different forms of caving pits on the surface. This phenomenon is called ground collapse. The subsidence area is often accompanied by a number of cracks around the collapse pit, forming annular or arc cracks of different sizes [19]. Because of the unevenness of the subsidence, sometimes some undulating humps or irregular cracks are formed in the subsidence area. Earthquake disasters can cause the ground collapse of graded highways, and ground collapse is one of the factors causing earthquake disasters on graded highways. The evaluation methods of ground collapse are shown in Table 4.

Table 4. Evaluation method of ground collapse.

Scale type*	Giant	Large	Medium	Small
Collapse pit diameter D (m)	D≥50	50>D≥30	30>D≥10	D<10
Area of influence S (km^2)	S≥20	20>S≥10	10>S≥1	S<1

Note: * indicates that if the evaluation grades of “Collapse pit diameter” and “Area of influence” are inconsistent, the higher grade shall prevail.

The evaluation method of ground collapse disaster is determined by two indexes, namely, collapse pit diameter and collapse area, which can clearly define the scope and influence degree of ground subsidence disaster respectively. For graded highway toughness evaluation, collapse pit diameter and collapse area are the best indexes for disaster evaluation in the case of single ground collapse disaster.

2.6. Surface Foreign

Surface foreign refers to the phenomenon of buildings, trees, equipment and other damage caused by earthquakes, which is scattered on the road and obstructs traffic operation [20]. According to the engineering experience of clear road surface foreign matter, the square amount of surface foreign matter is an important index for evaluating the seismic toughness of road sections and one of the earthquake disaster factors of graded highways. The evaluation method is shown in Table 5.

Table 5. Evaluation methods of surface foreign.

Grade	Landslide (m^3)
Giant	≥1000
Large	100-1000
Medium	10-100
Small	<10

It is concluded that the disaster factors of reducing the capacity of graded highway sections caused by earthquake mainly include: underground void, landslide, collapse, debris flow, ground crack, ground subsidence, ground collapse, surface foreign. These disaster factors are important aspects of earthquake disaster resilience evaluation of graded highway sections. Single consistent disaster factors can be combined with their own characteristics to establish the corresponding evaluation criteria.

3. Comprehensive Toughness Evaluation Method

The impact of single consistent disaster factors on the toughness of graded highway sections can be evaluated according to the appropriate evaluation method of the disaster itself, but in the actual evaluation, multiple disaster-causing factors often coexist. The toughness evaluation of graded highway sections should be unified and comprehensive when multiple disaster-causing factors appear at the same time.

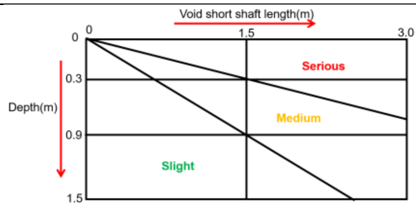
3.1. Relationship between Degree of Disaster-Causing Factors and Toughness

The single consistent disaster factor can extract the evaluation index according to the characteristics of disaster factors, and further establish the hierarchical evaluation system. There is a correlation between the graded evaluation of disaster-causing factors and the toughness of graded highways, and there is also a correlation between the degree of damage caused by disaster-causing factors to traffic capacity and the graded evaluation of disaster-causing factors. The higher the evaluation level of a consistent disaster factor is, the more serious the damage to the traffic capacity of graded highways caused by disaster factors will be, and the longer the repair time will be.

The toughness classification evaluation of graded highway is made according to the time of vehicles passing through the disaffected section. When road material damage, structural damage and function loss can be caused by the release, landslide, collapse, debris flow, ground crack, ground subsidence, ground collapse and surface foreign matter, emergency departments, construction units and other departments need to use construction machinery to repair the road section. Depending on the extent of the damage, it takes a certain amount of time to restore the capacity of the road section. Through extensive investigation of emergency construction personnel, it is possible to obtain the approximate time required to repair disaster factors. The traffic capacity of graded highways that can be restored after simple repair belongs to smooth passing after an earthquake; most traffic capacity of graded highways that can be restored after a period of time belongs to slow passing after an earthquake; while part of the traffic capacity of graded highways that can be restored after a longer period of time belongs to difficult passing after an earthquake.

In this paper, the single consistent disaster factor evaluation method is used to carry out the hierarchical evaluation of the single consistent disaster factor. According to the traffic capacity of highway sections at grade level, it can be summarized into three categories: smooth passage, slow passage and difficult passage. The evaluation index of each level is consistent with the evaluation index of a single consistent disaster factor. Table 6 shows the evaluation grading of single consistent disaster factors.

Table 6. Single consistent disaster factor evaluation methods.

<table>
<tr><th colspan="2">Scale type*</th><th rowspan="2">Difficult cross</th><th rowspan="2">Slow cross</th><th rowspan="2">Smooth cross</th></tr>
<tr><th>Disaster causing factor</th><th>Evaluation index</th></tr>
<tr><td>Underground void</td><td>Void short shaft length (m)
Depth (m)</td><td colspan="3">

Slight-Smooth; Medium-Slow cross; Serious-Difficult cross</td></tr>
<tr><td>Landslide</td><td>Square quantity (10^4m^3)</td><td>≥100</td><td>10-100</td><td><10</td></tr>
<tr><td>Collapse</td><td>Square quantity (10^4m^3)</td><td>≥10</td><td>1-10</td><td><1</td></tr>
<tr><td>Debris flow</td><td>Square quantity (10^4m^3)</td><td>≥20</td><td>2-20</td><td><2</td></tr>
<tr><td rowspan="2">Ground fracture</td><td>Cumulative length L (m)</td><td>L≥10000</td><td>10000>L≥100</td><td>L<100</td></tr>
<tr><td>Affected area S (km^2)</td><td>S≥10</td><td>10>S≥1</td><td>S<1</td></tr>
<tr><td rowspan="2">Land subsidence</td><td>Accumulated settlement h (m)</td><td>h≥1.0</td><td>1.0>h≥0.1</td><td>h<0.1</td></tr>
<tr><td>Settlement area S (km^2)</td><td>S≥500</td><td>500>S≥10</td><td>S<10</td></tr>
<tr><td rowspan="2">Ground collapse</td><td>Collapse pit diameter D (m)</td><td>D≥30</td><td>30>D≥10</td><td>D<10</td></tr>
<tr><td>Affected area S (km^2)</td><td>S≥10</td><td>10>S≥1</td><td>S<1</td></tr>
<tr><td>Surface foreign</td><td>Cubic quantity (m^3)</td><td>≥1000</td><td>10-1000</td><td><10</td></tr>
</table>

Note: * indicates that if the index evaluation grade is inconsistent, the higher grade shall prevail.

According to the grading standards of evaluation indexes of different disaster factors shown in Table 6, the toughness evaluation of disaster factors of graded highway sections can be realized. A smooth cross is worth 4 points, a slow cross is worth 7 points, a difficult cross is worth 10 points, and a perfect score for resilience is 100 points. The graded highway toughness was reduced according to the types and grades of disaster factors. The higher the graded highway toughness evaluation score, the better the traffic capacity, and the lower the graded highway toughness evaluation score, the worse the traffic capacity. When multiple disaster causing factors occur at the same time, the calculation method of earthquake toughness evaluation of graded highway sections is shown in equation (1).

$$\mathrm{T_z} = 100 - \sum(\mathrm{F_t} + \mathrm{F_{hp}} + \mathrm{F_b} + \mathrm{F_n} + \mathrm{F_l} + \mathrm{F_c} + \mathrm{F_{tt}} + \mathrm{F_y}) \quad (1)$$

In equation (1), T_z represents the evaluation index of graded highway disaster factors. F_t represents the graded evaluation assignment of the disaster factor of cavitation. F_{hp} represents the graded evaluation assignment of landslide disaster factors. F_b represents the graded evaluation assignment of disaster factors caused by the collapse. F_n represents the graded evaluation assignment of debris flow disaster factors. F_l represents the graded evaluation assignment of ground fracture disaster factors. F_c represents the graded evaluation assignment of land subsidence disaster factors. F_{tt} represents the graded evaluation value of a single ground collapse direct disaster. F_y represents the grading evaluation assignment of surface foreign body disaster factors.

3.2. Toughness Evaluation Method Considering the Number of Lanes

The number of lanes is an important index affecting the toughness of graded highway sections. The small number of lanes indicates narrow section width, large construction difficulty after the earthquake disaster, small engineering operation surface, long time required in the process of emergency treatment, relatively poor section toughness, graded highway section toughness evaluation score is low. When the number of lanes is more, the width of the road section is wider, the construction difficulty is less, the engineering operation surface is larger, the time required in the emergency treatment process is short, the toughness of the road section is relatively good, and the toughness evaluation score of the graded highway section is high. In most graded highways in our country, the number of lanes is 1 lane, 2 lanes, 3 lanes and 4 lanes. In this paper, combined with the actual emergency treatment engineering experience, the toughness evaluation weight coefficient of 1-lane graded highway section is set as 1, the toughness evaluation weight coefficient of 2-lane graded highway section is set as 0.8, the toughness evaluation weight coefficient of 3-lane graded highway section is set as 0.6, and the toughness evaluation weight coefficient of 4-lane graded highway section is set as 0.4. The toughness evaluation method of graded highway sections is shown in equation (2).

$$T = a_i \times T_Z \quad (2)$$

In equation (2), T represents the toughness evaluation index of graded highway sections; a_i represents the weight coefficient of lanes for toughness evaluation of graded highway sections; i represents the number of lanes, $a_1=1$, $a_2=0.8$, $a_3=0.6$, $a_4=0.4$; T_z represents the evaluation index of disaster factors of graded highways.

To sum up, the single consistent disaster factors can be graded and evaluated. According to the traffic capacity of graded highway sections, they can be classified into three categories: smooth passage, slow passage and difficult passage. The evaluation indexes of each level are consistent with those of the single consistent disaster factors. In the process of graded highway section toughness evaluation, the number of lanes is an important index affecting the toughness of the section. The weight coefficient can be used to evaluate the seismic toughness of graded highway according to the number of lanes of the graded highway.

4. Conclusion

(1) Graded highway is an important object of regional toughness evaluation. When earthquake disasters occur, it is necessary to evaluate the toughness of graded highway sections in disaster areas, so as to formulate the best emergency rescue plan.

(2) The disaster factors of the reduced capacity of graded highway sections caused by earthquake mainly include: underground void, landslide, collapse, debris flow, ground cracks, ground subsidence, ground collapse, surface foreign. These disaster factors are important aspects of earthquake disaster resilience evaluation of graded highway sections. Single consistent disaster factors can be combined with their own characteristics to establish the corresponding evaluation criteria.

(3) The single consistent disaster factor can be classified into three categories according to the traffic capacity of graded highway sections: smooth passage, slow passage and difficult passage. The evaluation index of each level is consistent with that of the single consistent disaster factor. In the process of graded highway section toughness evaluation, the number of lanes is an important index affecting the toughness of the section. The weight coefficient can be used to evaluate the seismic toughness of graded highway according to the number of lanes of the graded highway.

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