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青海门源 M_s 6.9 地震同震破裂的隧道破坏效应与启示

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The tunnel damage effects and implications of the coseismic rupture of the Menyuan M_s 6.9 Earthquake in Qinghai, China

Abstract: On January 8, 2022, a magnitude 6.9 earthquake occurred in Menyuan County, Qinghai Province, causing severe deformation and damage to the Da Liang Tunnel of the Lanzhou–Xinjiang high-speed railway, which is the first railway tunnel project broken by strike-slip earthquake in China. Through comprehensive analysis of field investigation data, InSAR surface deformation data, and monitoring results from the track control network (CPⅢ), this study delves into the characteristics of deformation and damage caused by the coseismic rupture zone of the Menyuan M_s 6.9 earthquake on the Daliang Tunnel. The results indicate that the Haiyuan Fault Zone's Lenglongling–Tuolaishan fault segment is the seismogenic fault for this earthquake, forming a coseismic surface rupture zone approximately 21.5 km long. The dominant deformation nature is left-lateral strike-slip, with a maximum left-lateral displacement of about 3.1 m. As the coseismic rupture zone intersects the Daliang Tunnel, it severely damages the tunnel structure, with the most intense deformation and damage concentrated within 60 m on either side of the central rupture zone. Comparing the observed tunnel deformation with the characteristics of coseismic surface rupture deformation, it is evident that the maximum vertical displacement across the fault zone in the tunnel area is approximately 91.6 cm, with a maximum left-lateral offset of about 2.88 m. The angle between the Lenglongling fault and the Daliang Tunnel is approximately 60°, and the calculated maximum left-lateral offset of the seismogenic fault is about 3.08 m. This indicates a close alignment between the maximum slip offset from coseismic surface rupture and the fault's maximum offset across the tunnel, suggesting that the tunnel structure struggles to resist significant coseismic deformations. The findings of this study can serve as a scientific reference for the planning, construction, and seismic damage prevention of railway projects crossing active fault zones.

Keywords: Menyuan earthquake; Daliang tunnel of the Lanzhou–Xinjiang high-speed railway; Lenglongling–Tuolaishan section of the Haiyuan fault; coseismic surface rupture; railway tunnel earthquake damage

摘要：2022年1月8日青海省门源发生 M_s 6.9 地震，导致兰新高铁大梁隧道发生严重变形破坏。综合野外调查资料、InSAR 地表变形数据及轨道控制网（CPⅢ）监测结果等，深入研究了青海门源 M_s 6.9 地震同震破裂带对兰新高铁大梁隧道造成的变形破坏特征。结果表明，海原断裂带冷龙岭–托莱山断裂段为此次地震的发震断裂，并形成长约 21.5 km 的同震地表破裂，变形性质以左旋走滑为主，地表的最大左旋位移约为 3.1 m。同震破裂带在穿过大梁隧道部位时，导致隧道工程发生严重损坏，最严重的变形破坏集中在主破裂带两侧各 60 m 范围内。对比隧道变形量观测结果和同震地表破裂变形特征可知，隧道区跨断裂的最大垂直位移约为 91.6 cm，最大左旋位错量约为 2.88 m，冷龙岭断裂与大梁隧道夹角约为 60°，经换

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算后对应的发震断裂最大左旋位错量约为3.08 m, 指示同震地表破裂的最大走滑位错量与穿过隧道的断裂最大位错量基本一致, 表明隧道工程在显著的同震变形中难以起到抗断作用。此次研究成果可为类似穿越活动断裂带的铁路工程规划建设及震害防治提供科学参考与借鉴。

关键词: 门源地震; 兰新高铁大梁隧道; 海原断裂带冷龙岭-托莱山段; 同震地表破裂; 铁路隧道震害

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0 引言

新生代期间中国大陆在欧亚板块、印度板块和西太平洋板块的夹持之下, 随着周边板块的持续俯冲与碰撞, 发育了复杂的活断层体系(Molnar et al., 1975; Zhang et al., 2004)。因而, 中国大陆强震频发, 是全球陆内活断层相关灾害最为严重的国家之一(张培震等, 2013)。在复杂的活动构造环境下, 公路、铁路、大型水电工程坝址和核电设施等重要基础设施和工程常常面临如何科学规避或防范活断层灾害及其风险的问题(李玶和苑京立, 1983; Sunil et al., 1992; 崔臻等, 2013; 马映辉等, 2021; 孟秋等, 2021; 吴中海, 2019, 2022; 张林成等, 2022)。

随着中国西部铁路工程建设的快速发展, 穿越活动断裂的铁路隧道不断增多, 如穿越海原断裂带的冷龙岭-托莱山断裂段的兰新高铁大梁隧道。据中国地震台网记录(<https://news.ceic.ac.cn/CC20220108014528.html>), 2022年1月8日青海门源县发生 M_s 6.9地震, 震中位于37.77°N、101.26°E。此次地震发生在青藏高原东北缘主边界走滑断裂带——海原断裂带的冷龙岭-托莱山断裂段上(Guo et al., 2022; 韩帅等, 2022), 震中距兰新高铁约为4.5 km, 因同震主破裂带穿过大梁隧道出口段, 造成了高铁断道, 属于一例走滑型发震断裂错断铁路隧桥的工程事件。目前研究重点为地震同震破裂下铁路隧道的震害形成机制以及定性预测同震破裂造成的隧道工程深部变形特征(张玉敏等, 2013; 高峰等, 2015; 崔光耀等, 2018; 方林等, 2019; Chen et al., 2022)。工程实例的缺乏以及震前、震后变形高精度观测数据的不足, 制约了有关同震破裂对隧道工程影响的研究和评价。

门源 M_s 6.9地震同震破裂错断兰新高铁大梁隧道为研究提供了工程实例, 并且获得了穿越隧道的活动断裂两侧高精度的震前、震后位移数据。在地表调查基础上, 基于高精度观测数据对同震破裂引发的大梁隧道破坏效应进行研究具有重要科学

意义和应用价值, 并可为跨活动断裂铁路工程选线和抗震设防提供宝贵的工程案例。

1 地震构造背景

兰新高铁大梁隧道地处青藏高原东北缘祁连山弧形造山带的前缘, 构造变形强烈、褶皱与断裂发育, 构造线整体以北西向和北西西向为主(周民都等, 2000; 潘桂棠等, 2002)。第四纪期间, 青藏高原的持续向北推挤作用导致该区发育了一系列以北西西向压扭变形为主的活动断裂带(袁道阳等, 2004; 张培震等, 2013; 姜文亮等, 2017; 王鑫等, 2020)。

位于青藏高原东北缘边界的北西西向—北西向海原断裂带为大梁隧道区段最主要的控震构造带, 也是调节青藏高原东北缘地壳缩短和块体向东挤出的主要活动构造带(Gaudemer et al., 1995; Tapponniere et al., 2001; 郭鹏等, 2017; 雷东宁等, 2018; 徐化超, 2019; 薛善余等, 2022)。此次门源 M_s 6.9地震的发震断裂即为海原断裂带的冷龙岭-托莱山断裂段(韩帅等, 2022; 焦其松等, 2022), 该段断裂大致沿东祁连山山脉分水岭分布, 全长约为123 km, 总体走向NW60°—80°, 为全新世活动断裂, 晚第四纪其左旋走滑速率约为15~19 mm/a(何文贵等, 2010; 张培震等, 2013; Chen et al., 2023)。兰新高铁大梁隧道穿越该断裂(图1)。

门源 M_s 6.9地震最大水平错动位移约为3.1 m, 最大垂直位错约为0.8 m(盖海龙等, 2022)。综合高分辨率卫星影像详细解译和破裂带的野外调查, 在海原断裂带中厘定出两条呈左阶斜列、北西西—南东东走向的地震同震破裂带(图2)。一条发育在托来山断裂的东段, 总长约为3.8 km, 以左旋走滑变形为主, 局部兼向南逆冲性质, 最大走滑位移约为0.5 m。另一条发育在冷龙岭断裂的中—西段, 为此次地震的主破裂带, 呈北东向微凸的弧形展布, 全长约为21.5 km, 整体以左旋走滑变形为主兼向北逆冲性质, 最大走滑位移约为3.1 m, 与已有实测数据(盖

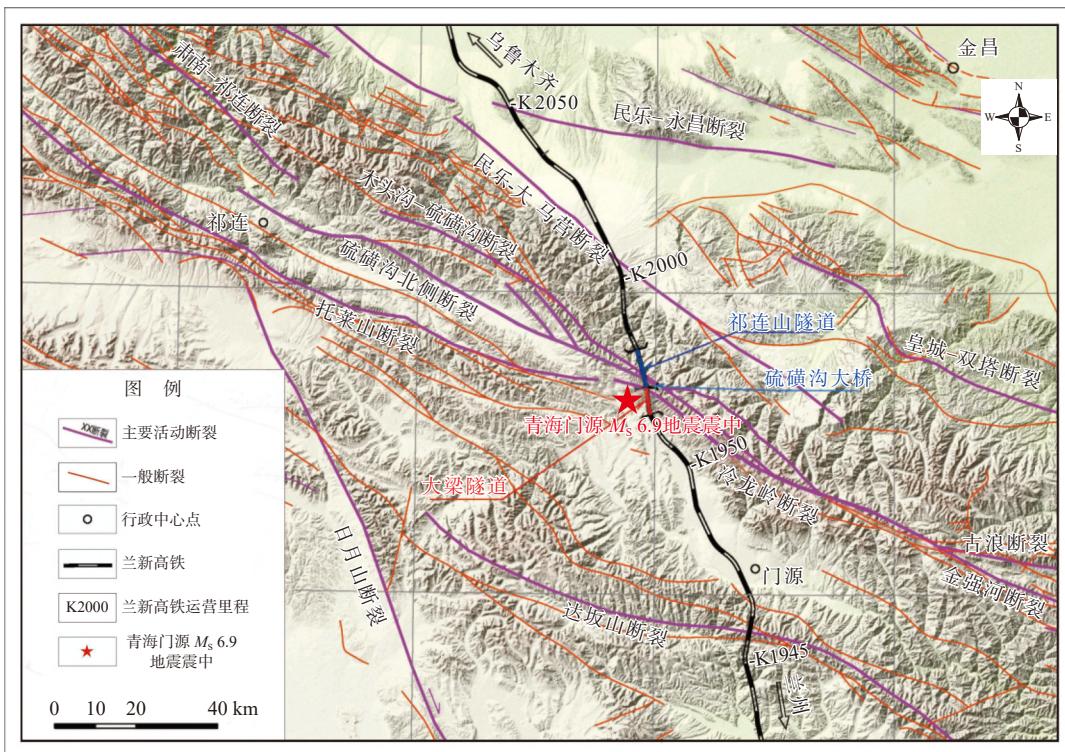


图 1 兰新高铁大梁隧道位置和区域主要活动断裂分布图

Fig. 1 Map of the location of the Daliang Tunnel and the distribution of major active faults in the area

海龙等, 2022)一致。地表破裂表现最明显区段与兰新铁路大梁隧道呈大角度相交并穿过隧道(韩帅等, 2022; 潘家伟等, 2022), 导致其 K1971+341—K1971+691 里程段的结构破损严重。地表破裂变形主要表现为剪切裂缝、雁列状挤压脊、拉张裂隙和断坎等多种类型(图 3)。铁轨、洞壁及路基等发生强烈的缩短隆起和走滑位错等变形; 同时, 隧道北侧的硫磺沟大桥与桥墩也发生了不同程度的变形和倾斜变位。

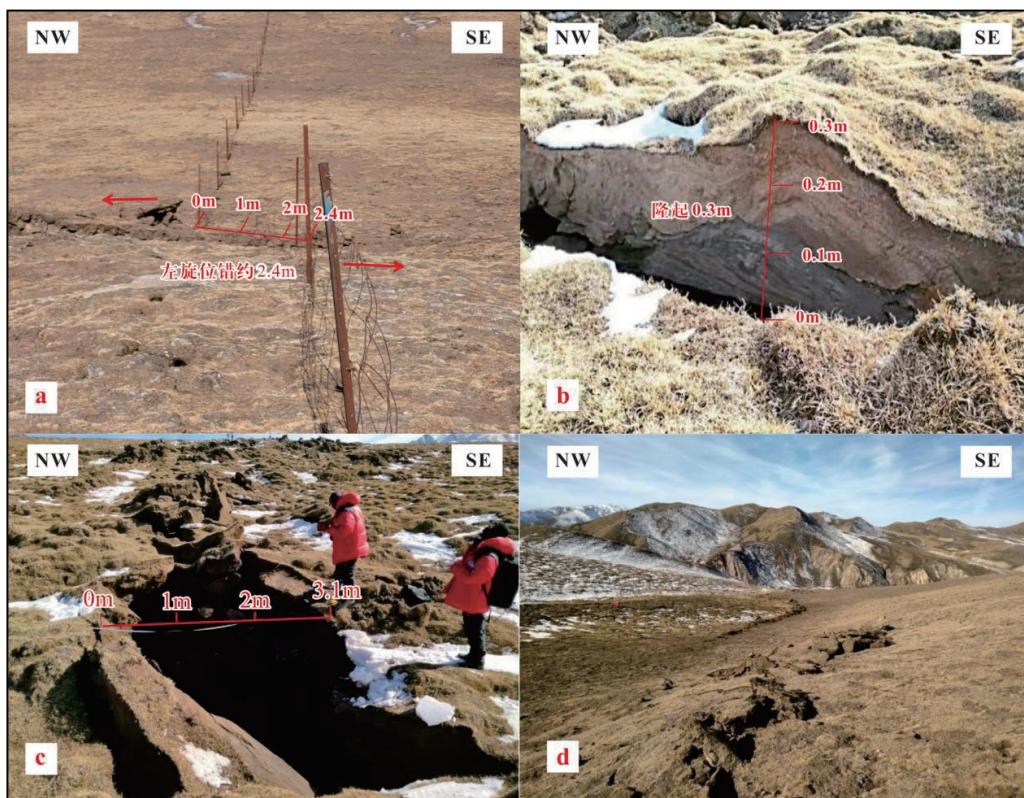
2 D-InSAR 揭示的同震地表形变特征

文章获取了震前 2021 年 12 月 29 日和震后 2022 年 1 月 10 日覆盖整个破裂区的分辨率为 20 m 的 Sentinel-1 雷达卫星数据。采用差分干涉测量(D-InSAR)技术对破裂区的地表形变状况进行计算, 得到破裂区的同震形变图(图 4)。结果显示, 此次地震的形变范围达到 30 km×30 km 以上, 发震断裂为



图 2 青海门源 M_s 6.9 地震同震地表破裂带分布图

Fig. 2 Distribution map of the coseismic surface rupture zones for the Menyuan M_s 6.9 Earthquake in Qinghai



a—铁丝网围栏左旋错位; b—地表破裂形成的地震陡坎; c—张裂缝; d—左阶雁行状挤压鼓包

图 3 海原断裂带冷龙岭—托莱山断裂段同震地表破裂 (具体位置见图 2)

Fig. 3 Coseismic surface ruptures of the Lenglongling–Tuolaishan fault in the Haiyuan fault zone (The location is shown in Fig. 2)

(a) Left-lateral displacement of wire mesh fence; (b) Seismic scarp formed by surface rupture; (c) Tensile crack; (d) left echelon compressional bulge

海原断裂带冷龙岭—托莱山断裂段，并显示断裂北盘沉降、南盘抬升的形变特征。降轨影像卫星视线方向 (LOS) 南盘和北盘最大形变量约为 75 cm、-55 cm，升轨影像 LOS 方向南盘和北盘最大形变量分别约为 45 cm、-60 cm，升、降轨影像最大 LOS 方向形变量指示跨发震断裂的垂直变形幅度最大可达 135 cm。同震形变带主体沿北西西—南东东向的海原断裂带冷龙岭—托莱山断裂段展布，长度超过 20 km。

3 大梁隧道主要震害表现

由于发震断裂大角度切穿大梁隧道(图 5)，地表破裂和形变显著。大梁隧道 K1971+341—K1971+691 里程段震害表现最为严重，其次为 K1971+691—K1972+088(隧道出口)里程段，其余区间的震害相对轻微。

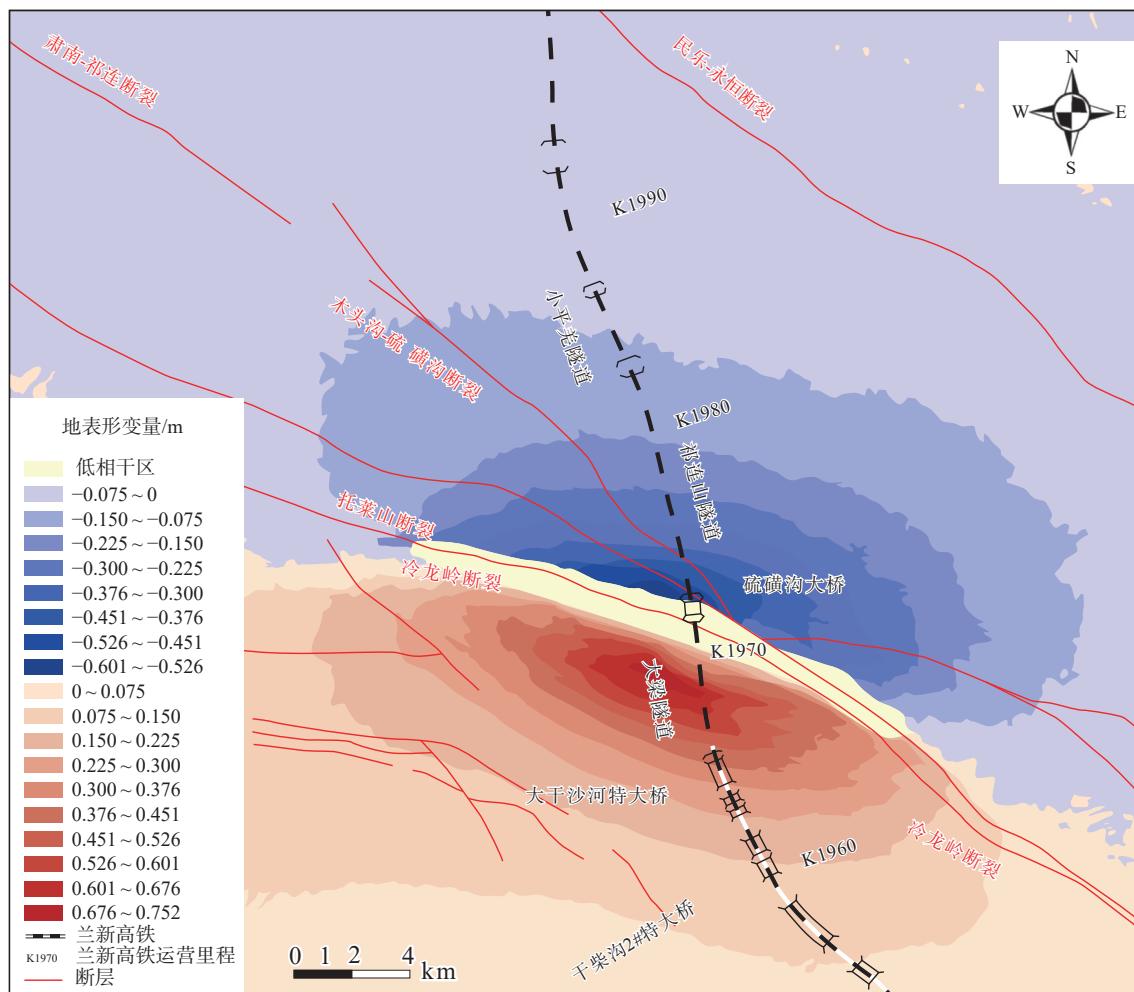
3.1 K1971+341—K1971+691 里程段的震害表现

该段的震害表现主要为同震破裂变形导致的

仰拱隆起、钢轨扭曲、边墙走滑位错及一些伴生破坏。其中仰拱沿隧道中线隆起高为 0.3~0.5 m，左、右线轨道板分别向两侧倾斜，倾角约为 40°，钢轨扭曲变形严重，两侧排水沟堵塞、盖板挤压隆起，水沟侧壁倾斜、局部破坏，电缆槽盖板挤压隆起、凹凸不平，衬砌环向挤压破坏，隔水层外露，隧道拱部大面积脱落，大量钢筋变形断裂外漏。在 K1971+400 里程前后各 60 m 范围内，隧道在横向和垂向上均发生了断错，其中隧道边墙错断出现在 K1971+390.4—K1971+411.7 里程段附近，最大错位处为里程 K1971+400，该处沿隧道横向(即垂直隧道轴向方向)发生左旋错动约为 2.88 m，沿隧道纵向(即平行隧道轴向方向)错动 0.2~0.7 m，同时可见 0.3~0.8 m 宽度不等的地裂缝发育(图 6)。

3.2 K1971+691—K1972+088(隧道出口)里程段的震害表现

该段震害主要表现为拱顶挤压破裂、道床隆起、衬砌与仰拱拉张破裂等(图 7)。其中，中间底



破裂带附近地表破裂或相对滑动剧烈,形成一定宽度的低相干区域,做掩膜处理

图 4 门源地震 D-InSAR 地表形变特征

Fig. 4 D-InSAR surface deformation map of the Menyuan earthquake

The surface rupture or relative slide near the fracture zone is severe, forming a low coherence area of a certain width, and masking is performed.



图 5 发震断裂大角度切穿大梁隧道

Fig. 5 The seismogenic fault cutting through the Daliang tunnel at a large angle

板的隆起变形幅度最大约为 0.5 m, 道床中心的仰拱填充面左旋错动为 7~8 cm, 并出现轨道板隆起和钢轨凸起变形。同时, 可见隧道底板两侧的盖板隆起、水沟侧壁破坏和拱部剥落掉块等现象, 最大剥落面积达 0.6 m², 局部出现渗漏水。

4 轨道控制网 (CPⅢ) 揭示的隧道变形

CPⅢ 是一种针对铁路轨道形变的观测方法, 在线下工程施工完成并通过沉降变形评估后实施观测, 可为轨道运营维护提供测量基准 (王道远等, 2019; 王国祥和赖鸿斌, 2012)。CPⅢ 按自由设站边角交会方法进行测量, 点间距纵向上为 60m, 横向上为线路结构物宽度, 测量精度为相邻点位的相对误差, 通常小于 1.0 mm。此次地震的发震断裂直接穿

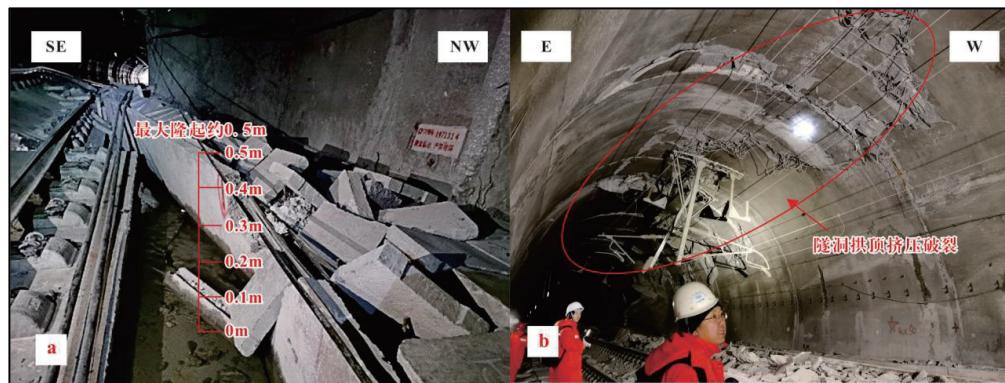


a—隧道断裂处云俯视图; b—隧道被断裂左旋错动实景(镜向北)

图 6 切穿大梁隧道的同震断裂及其破坏效应
Fig. 6 Coseismic fault cutting through the Daliang tunnel and its failure effect

(a) Top view of the tunnel rupture zone; (b) Actual scene of the tunnel subjected to left-lateral offset from the rupture (view facing north)

过大梁隧道, 断裂与大梁隧道相交于 K1971+400 里程处, 两者夹角约为 70° 。此次主要采用大梁隧道震前 2020 年 12 月的 CP III 观测数据和震后 CP III 复测结果, 将跨过大梁隧道 CP III 观测点北向、东向坐标变化值转换成沿铁路横向、垂向变化值后, 可获得沿大梁隧道线路震后的 CP III 平面变形量分布规律图(图 8); 并据此得到震后大梁隧道线路震后的 CP III 高程变形量分布规律图(图 9)。



a—道床板隆起变形; b—隧道拱顶挤压破裂

图 7 K1971+691—K1972+088 (隧道出口) 里程段的同震破坏效应

Fig. 7 Coseismic failure effect of the section from K1971+691 to K1972+088 (tunnel exit)

(a) Deformation with uplift of the bed plate; (b) Compression rupture on the tunnel arch

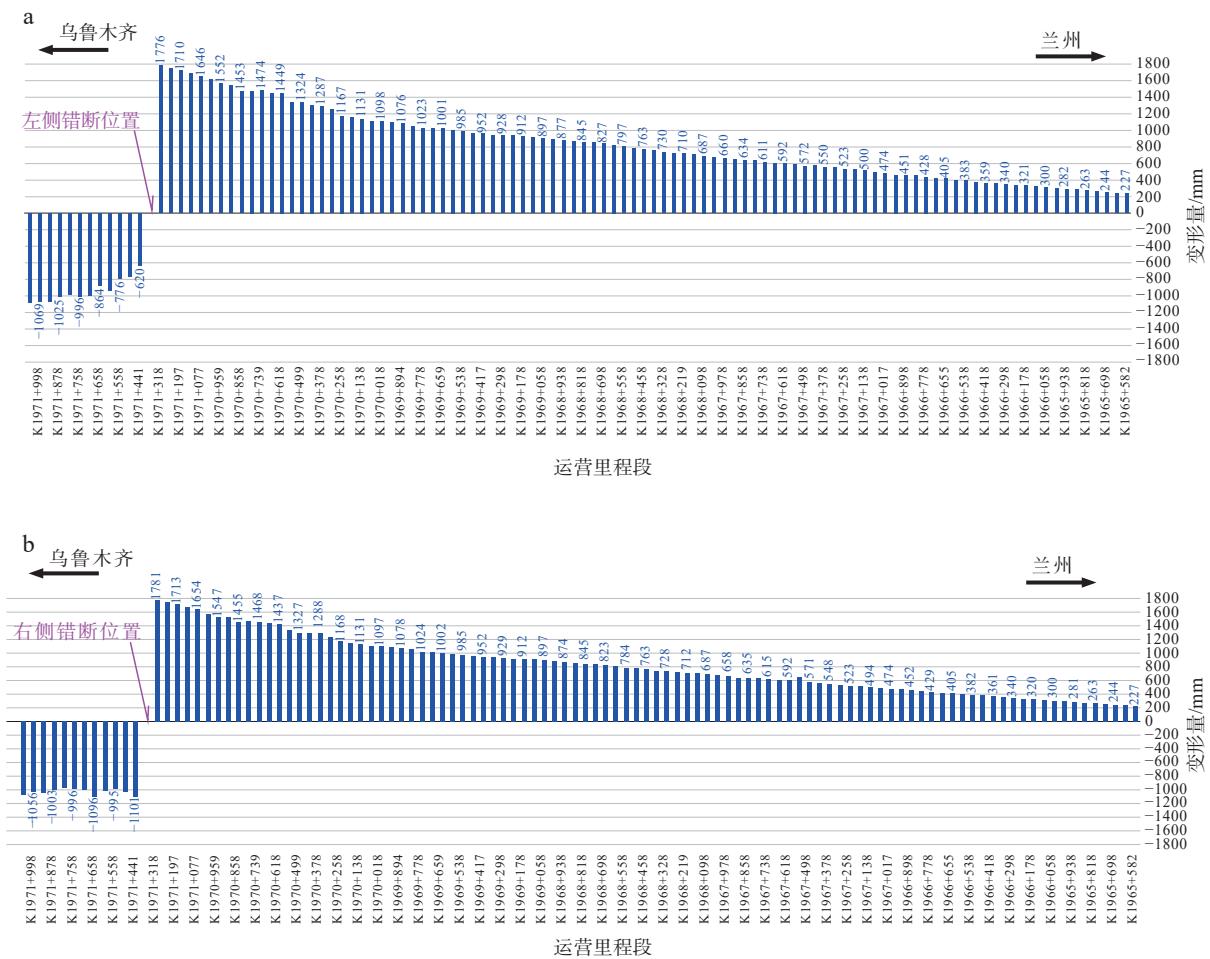
4.1 大梁隧道 CP III 平面测量数据分析

结果显示, 同震破裂导致大梁隧道发生显著的左旋位错。在主破裂带南侧, 从大梁隧道进口到 K1971+400 里程处, CP III 点位表现为向隧道右侧(即北东东方向)位移, 并且横向位移存在由小到大的变化, 位移量从 0.22 m 增大到 1.78 m; 在主破裂带北侧, 从 K1971+400 里程处到大梁隧道出口, CP III 点位表现为向隧道左侧(即南西西方向)位移, 横向位移量为 0.62~1.10 m。根据 CP III 观测结果, 大梁隧道最大左旋位错出现在 K1971+400 里程处, 最大位错量为主破裂带南、北两侧最大横向(即垂直隧道轴向方向)位移之和, 约为 2.88 m。

4.2 大梁隧道 CP III 高程测量数据分析

CP III 高程测量结果显示, 从大梁隧道进口到 K1971+400 里程处, 主破裂带南侧 CP III 高程均表现出向上抬升, 最大抬升量出现在 K1970+500 里程处, 达 68.7 cm; 主破裂带北侧 CP III 高程均表现出向下沉降, 最大沉降量出现在 K1971+558 里程处, 达 22.9 cm。主破裂带两侧的最大升、降量相加, 代表了此次同震破裂导致的隧道最大垂直位移量, 约为 91.6 cm。

综合隧道震害调查和 CP III 观测结果, 同震变形在大梁隧道段主要表现为左旋走滑兼由南向北逆冲, 造成主破裂带北盘沉降南盘抬升。隧道在 K1971+400 里程前后各 60 m 区间内的水平与垂向变形量最为显著, 最大水平错断(断距)出现在 K1971+400 里程处, 达 2.88 m, 考虑到海原断裂带的冷龙岭-托莱山断裂段与大梁隧道夹角约 60° , 断裂位移约等于 $2.9 \text{ m}/\cos 30^\circ$, 换算后对应的断裂最大左



“+”为向隧道右侧(即北东东方向)位移;“-”为向隧道左侧(南西西方向)位移

a—线路左侧(即隧道轴线西侧壁)CPⅢ平面变形量分布规律图;b—线路右侧(即隧道轴线东侧壁)CPⅢ平面变形量分布规律图

图 8 大梁隧道线路 CPⅢ 平面变形量分布规律图

Fig. 8 Distribution of CPⅢ plane deformation of the Daliang tunnel line

(a) Distribution of CPⅢ plane deformation on the left side of the line (the west side wall of the tunnel axis); (b) Distribution of CPⅢ plane deformation on the right side of the line (the eastern side wall of the tunnel axis)

“+” indicates displacement towards the right side of the tunnel (north-east direction), and “-” indicates displacement towards the left side of the tunnel (south-west direction).

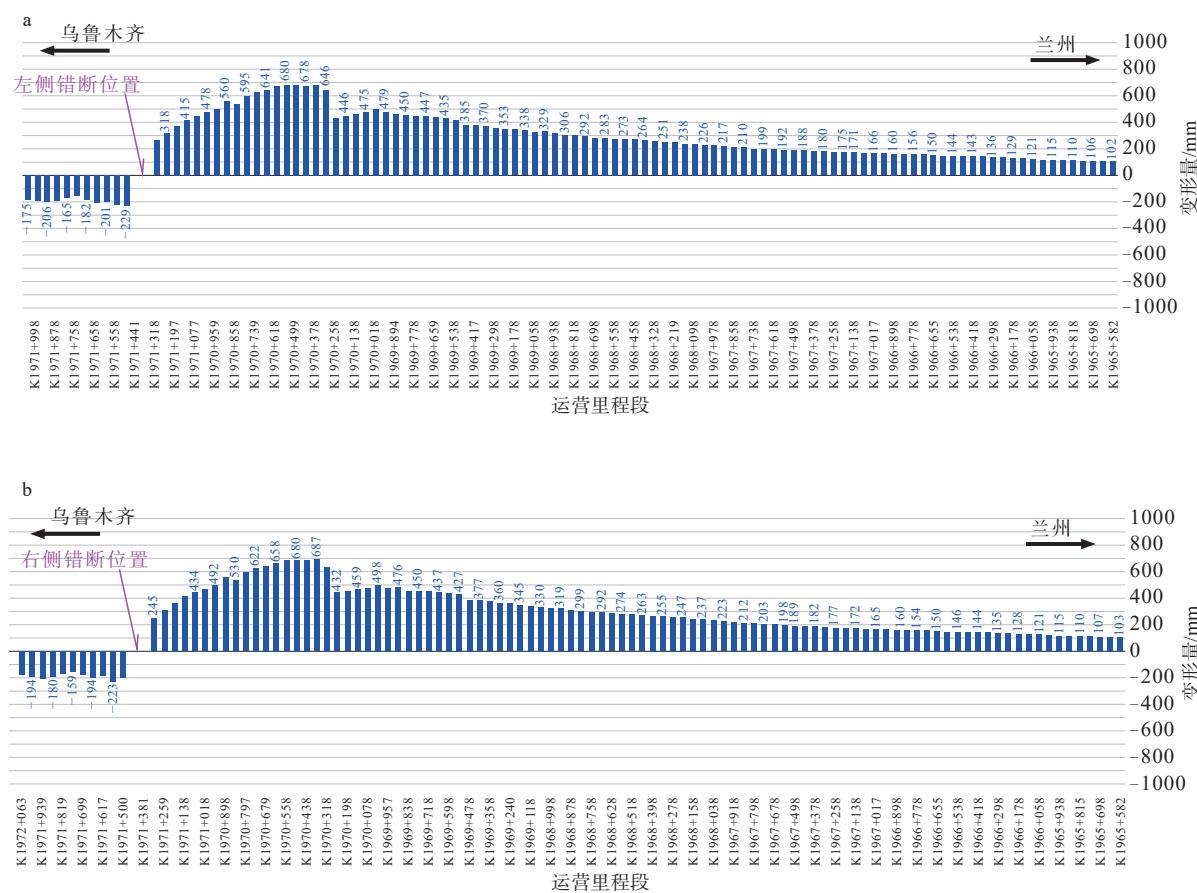
旋位错量约 3.08 m。(图 10)。

5 结论

(1) 青海门源 $M_s 6.9$ 地震的发震断裂为青藏高原东北缘海原断裂带的海原断裂带的冷龙岭-托莱山断裂段, 同震形变场主要沿北西西-南东东向发生破裂, 形成长度超过 20 km 的地表破裂带, 区域形变范围达到 30 km×30 km 以上, 发震断裂的变形特征以左旋走滑为主, 兼具有南北向逆冲性质, 造成破裂带以北地面沉降、以南地面抬升, 地表最大左旋位移约 3.1 m。

(2) 门源 $M_s 6.9$ 地震同震破裂变形最显著段落穿过兰新高铁大梁隧道, 造成隧道破坏严重, 隧道在里程 K1971+400 前后各 60 m 区间内的平面和垂向变形量明显, 最大垂直位移约为 91.6 cm, 最大左旋位错出现在里程 K1971+400 处, 约为 2.88 m, 考虑到海原断裂带冷龙岭-托莱山断裂段与大梁隧道夹角约为 60°, 换算后对应的断裂最大左旋位错量约为 3.08 m, 与地表的同震破裂最大位错量基本一致。

(3) 大梁隧道的同震破坏特征表明, 地震破裂对隧道的变形破坏严重且工程修复难度大, 说明隧道并非工程抗断的有效方式。因此, 在铁路工程选



“+”表示抬升量；“-”表示沉降量

a—线路左侧(即隧道轴线西侧壁)CP III 高程变形量分布规律图; b—线路右侧(即隧道轴线东侧壁)CP III 高程变形量分布规律图

图 9 大梁隧道线路 CP III 高程变形量分布规律图

Fig. 9 Distribution law of CP III elevation deformation of the Daliang tunnel line

(a) Distribution of CP III elevation deformation on the left side of the line (the west side wall of the tunnel axis); (b) Distribution of CP III elevation deformation on the right side of the line (the eastern side wall of the tunnel axis)

"+" represents uplift, and "-" represents subsidence.

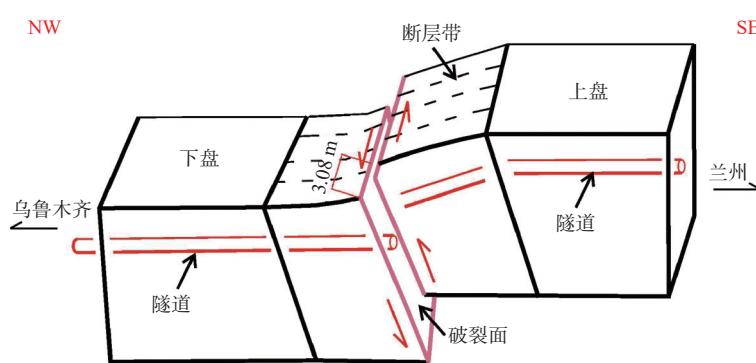


图 10 大梁隧道同震变形机制与破坏效应示意图

Fig. 10 Schematic diagram of coseismic deformation mechanism and failure effect of the Daliang tunnel

线设计中应避免采用隧道方式穿越相对危险的活动断裂带。鉴于区域内活动断裂带发育且强震相对频繁,建议在大梁隧道修复运营后,应加强跨活

动断裂带震后变形、工程场址地应力实时变化和隧道区地表裂缝等的实时监测,并构建立体监测系统平台,从而为保障铁路运营期的地震地质灾害风险

评价及科学防控提供全方位的技术支撑。

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