



如何合理布设GNSS站点—针对走滑断层的监测

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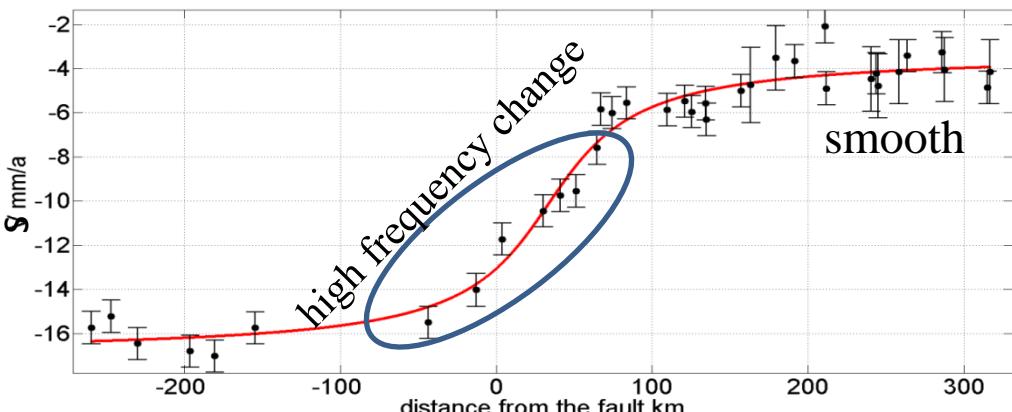


outline

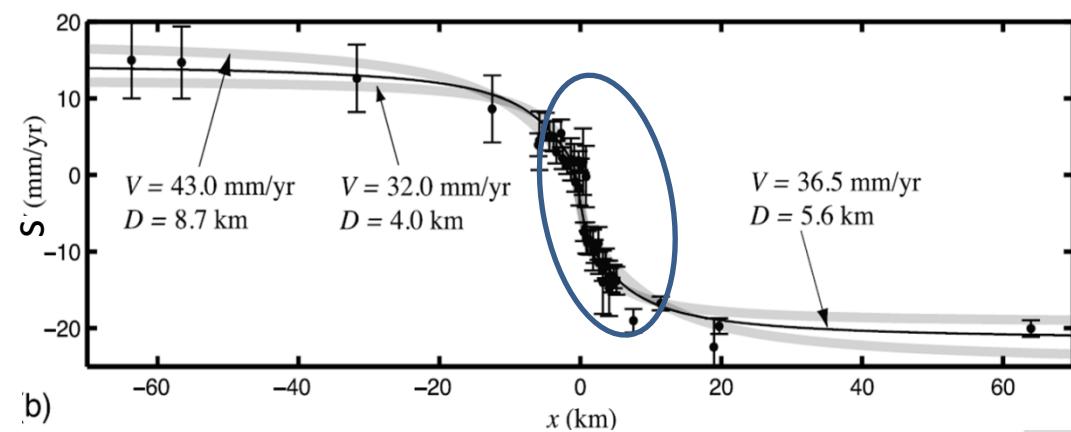
- Introduction
- How to do?
 - range
 - Interval/spacing
 - improved
- Results and discussion

Introduction

- Fault locking status can be retrieved by fault movement monitored by GPS data, and are significant to estimate the possible seismic hazard.
- Does the current GPS stations satisfy the monitoring of fault movement?



How to determine the optimum location of GPS stations in considering of **financial support** ?



Profile of San Andres Fault(Smth-Konter et al., 2010)

Two points:

(1) **range**

How far is the farthest location?

(2) **interval/spacing**

How far between two adjacent stations?



outline

- Introduction
- How to do?

range

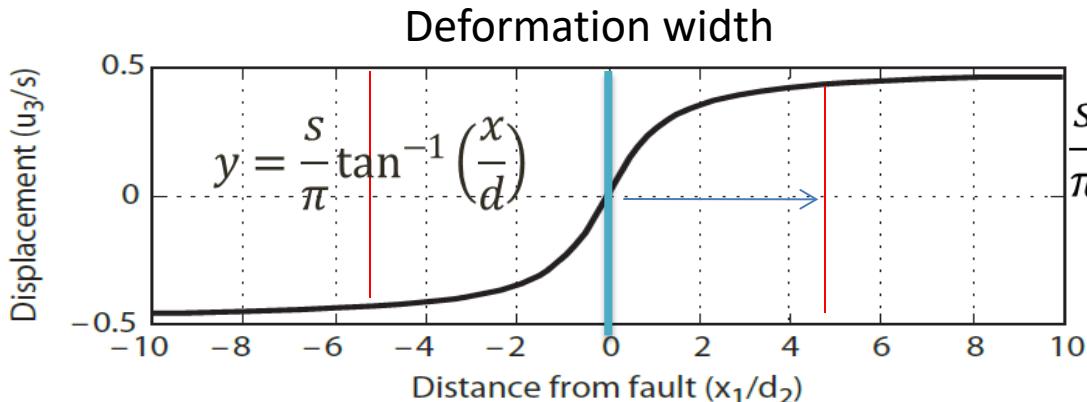
Interval/spacing

improved

- Results and discussion

(1) Range: 变形宽度

90% of the deformation of relative motion of the block (Wei, 2012 in Chinese)



model of inter-seismic strike-slip fault displacement

relative movement is concentrated close to the fault (e.g., 50% of the relative motion occurs between $x = -D$ and $x = +D$, but, to include 90% of the relative motion, measurements must be made across a zone extending from $x = -6.3D$ to $x = +6.3D$. Thus if D is about

(Savage and Burford, JGR, 1973)

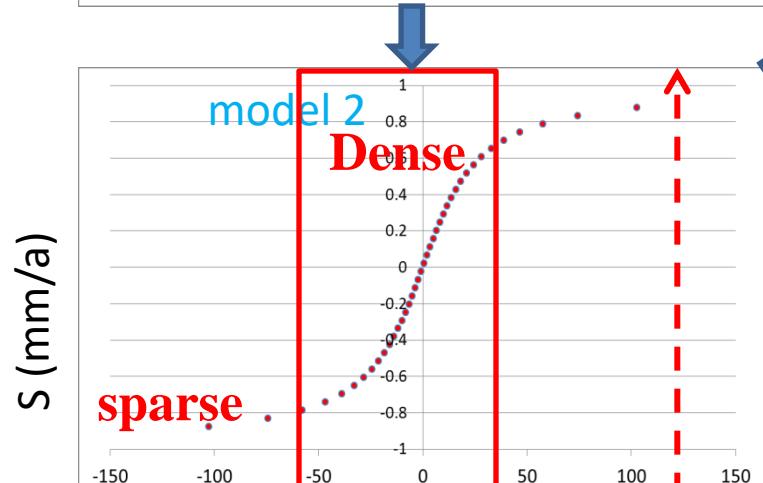
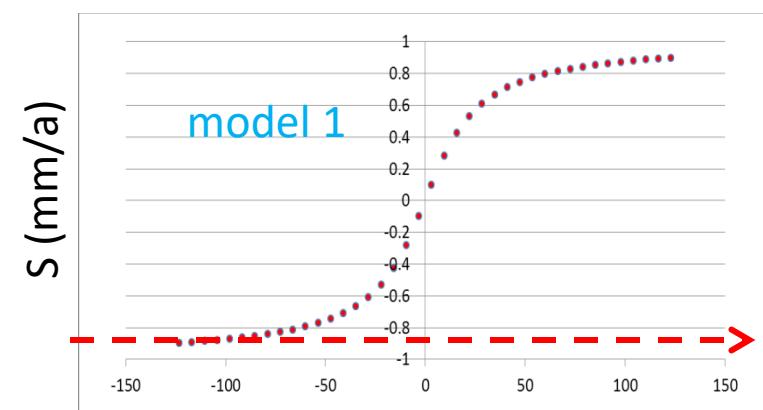
$$\frac{s}{\pi} \cdot \tan^{-1}\left(\frac{x_c}{d}\right) = \lim_{x \rightarrow \infty} \frac{s}{\pi} \cdot \tan^{-1}\left(\frac{x}{d}\right) \cdot 90\%$$

$$\Rightarrow \frac{s}{\pi} \cdot \tan^{-1}\left(\frac{x_c}{d}\right) = \frac{9s}{20}$$

$$x_c = \tan\left(\frac{9\pi}{20}\right) \cdot d \approx 6.31 \times d$$

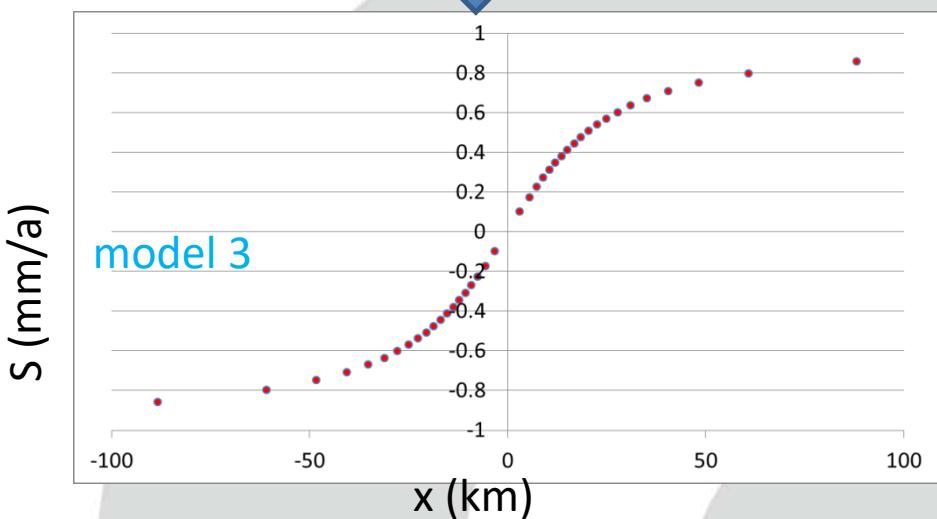
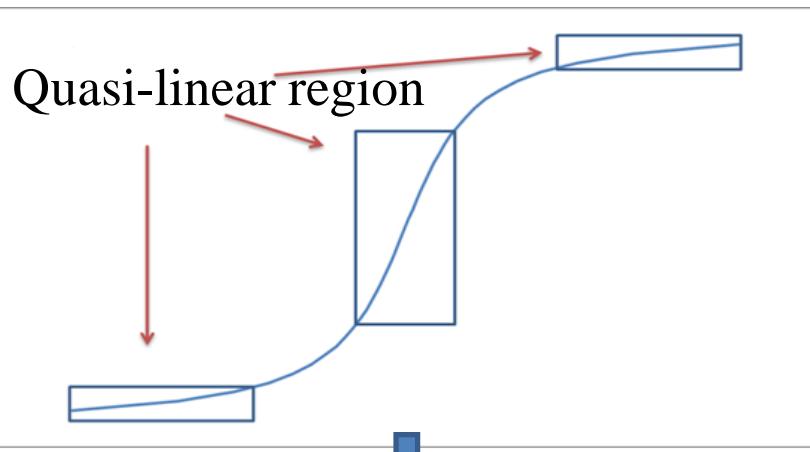
x_c 只与闭锁深度有关，
而与滑动速率无关

(2) interval/spacing



$$y = \frac{s}{\pi} \cdot \tan^{-1} \left(\frac{x}{d} \right)$$

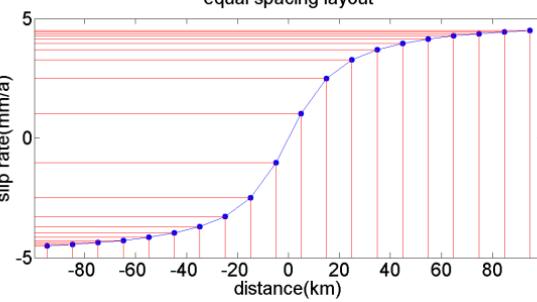
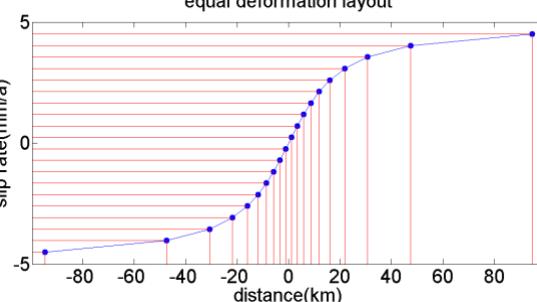
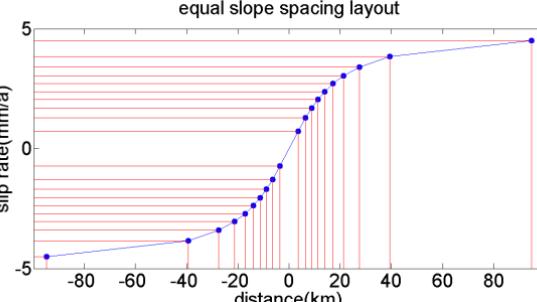
linear



$$y = \left(\frac{s}{\pi} \cdot \tan^{-1} \left(\frac{x}{d} \right) \right)' = \frac{s}{\pi d} \cdot \frac{1}{1 + \frac{x^2}{d^2}}$$

(2) interval/spacing

表 1

模式	布设模式	站点间隔
模式 1: 等间距布 设	<p style="text-align: center;">equal spacing layout</p> 	$x_{interval} = \frac{m \cdot d}{n} \cdot k$ $k = 1, 2, 3 \dots n$
模式 2: 等形变量 布设	<p style="text-align: center;">equal deformation layout</p> 	$x_{interval} = d \cdot \tan\left(\frac{k}{n} \cdot \tan^{-1}(m)\right)$ $k = 1, 2, 3 \dots n$
模式 3: 等斜率变 化布设	<p style="text-align: center;">equal slope spacing layout</p> 	$x_{interval} = d \cdot \sqrt{\frac{(m^2 + 1) \cdot n}{m^2 \cdot k} - 1}$ $k = n, \dots, 3, 2, 1$

(3) Improved

Non-linear

Non-linear layout for model 2

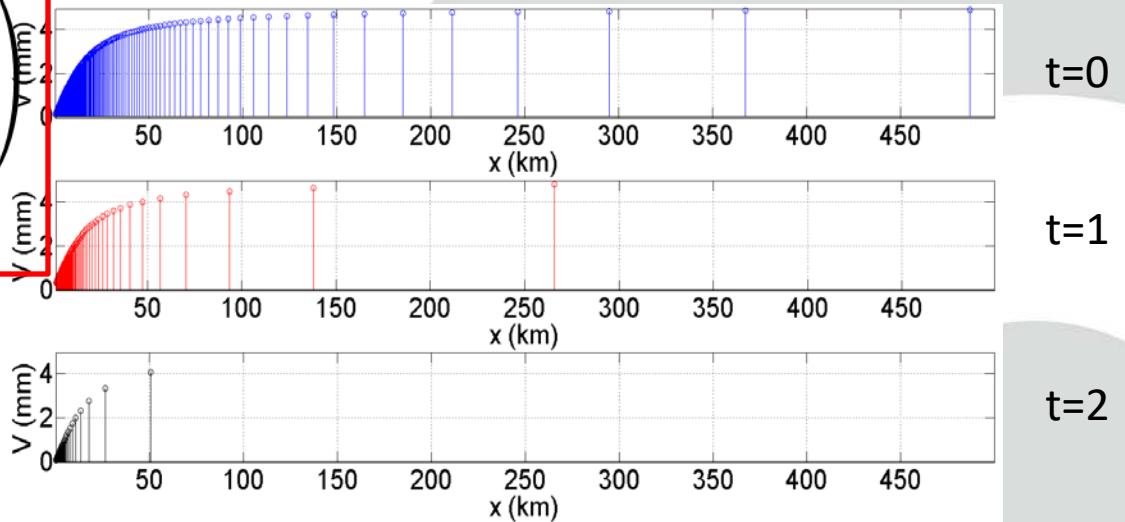
$$y = \frac{s}{\pi} \tan^{-1} \left(\frac{x}{d} \right) \Rightarrow y = f(x) \Rightarrow x = f^{-1}(y)$$

$$g(y) = s \cdot \tan^{-1} \left(\frac{y}{s \cdot d} \right)$$

$$x = f^{-1}(y) \cdot (g'(y))^t \quad y \in (0, s/2)$$

$$x = \frac{1}{d^{t-1}} \cdot \tan \left(\frac{k\pi}{n} \right) \cdot \left(\frac{1}{1 + \frac{k^2}{n^2 \cdot d^2}} \right)^t$$

$$k = 0, 1, 2 \dots n - 1$$



t is likely to be a real number, not only a integer

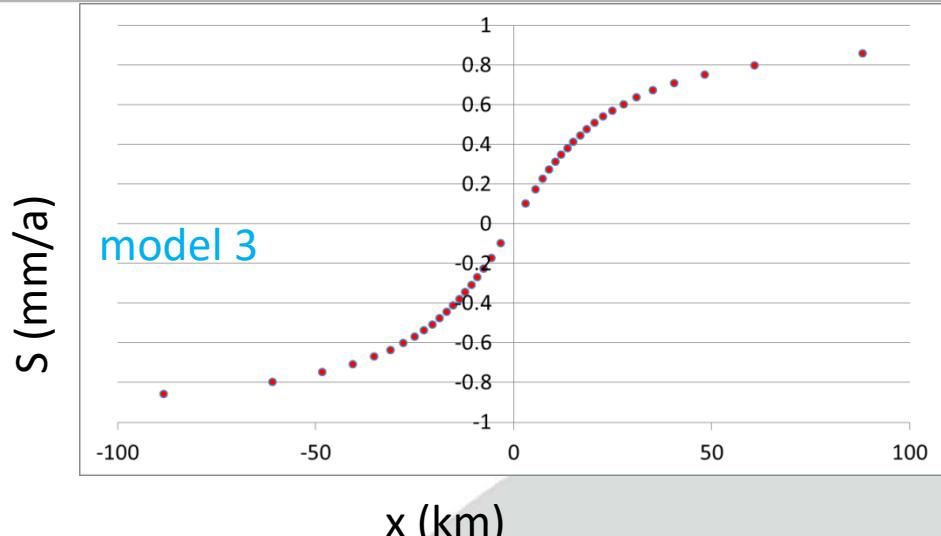
(3) improved

Non-linear layout for model 3

$$y = \left(\frac{s}{\pi} \tan^{-1} \left(\frac{x}{d} \right) \right)' = \frac{s}{\pi d} \cdot \frac{1}{1 + \frac{x^2}{d^2}}$$

similar

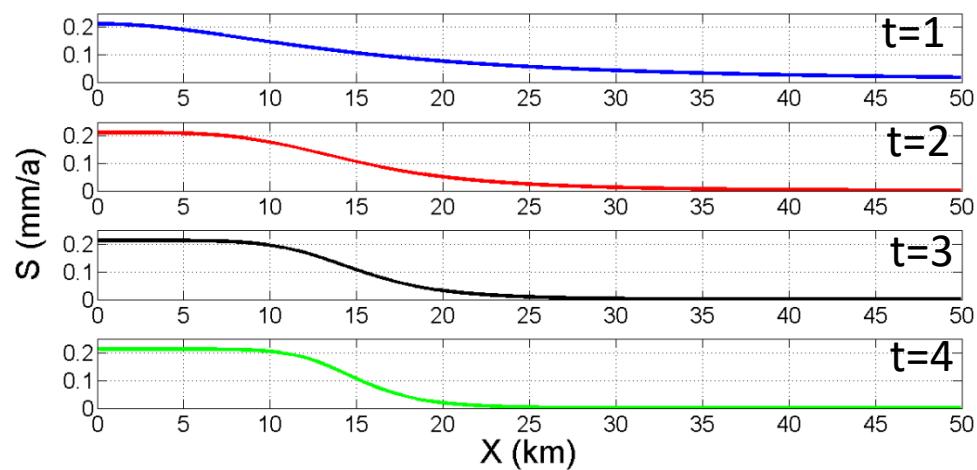
$$H(\omega) = \frac{1}{1 + \left(\frac{\omega^2}{\omega_c^2} \right)^n}$$



N-order Butterworth low-pass filter

$$y = \frac{s}{\pi d} \cdot \frac{1}{1 + \left(\frac{x^2}{d^2} \right)^t}$$

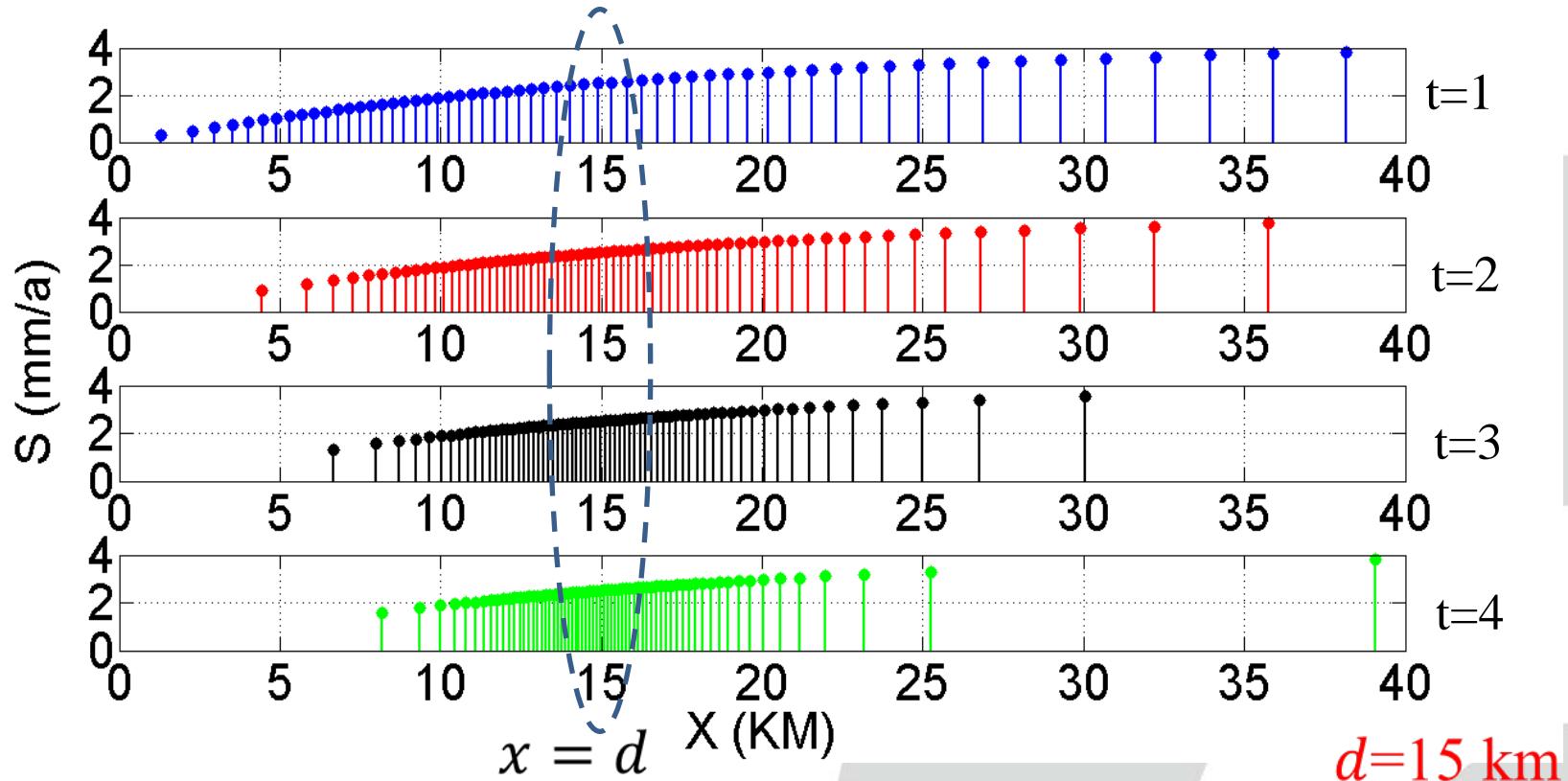
$$y \in (0, s/\pi d)$$



$x = d$

(3) improved

$$x = d \cdot \left(\frac{n - k}{k} \right)^{\frac{1}{2t}} \quad k = 1, 2, \dots, n$$



t is likely to be a real number, not only a integer



outline

- Introduction
- How to do?

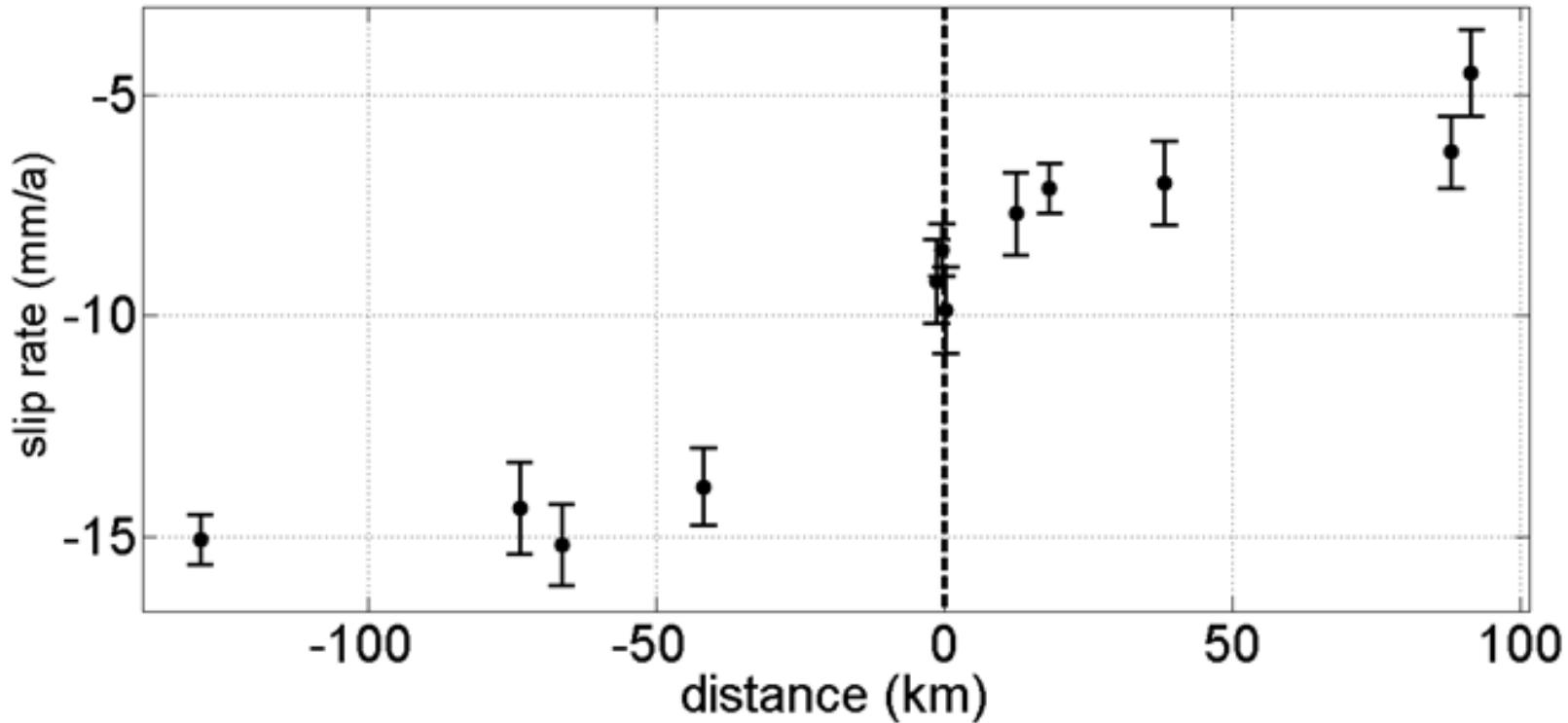
range

Interval/spacing

improved

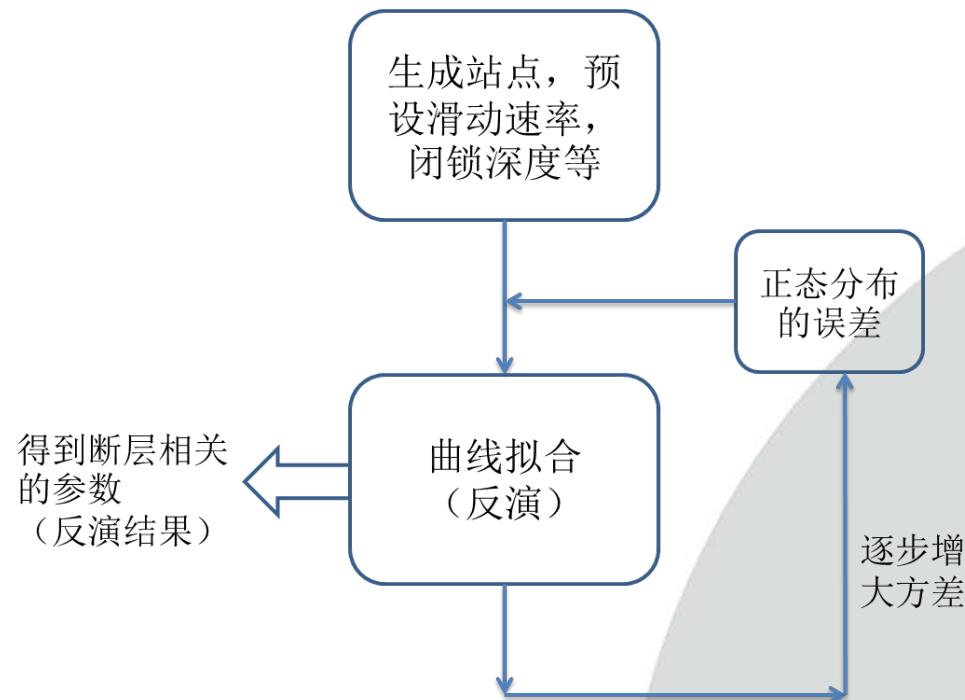
- Results and discussion

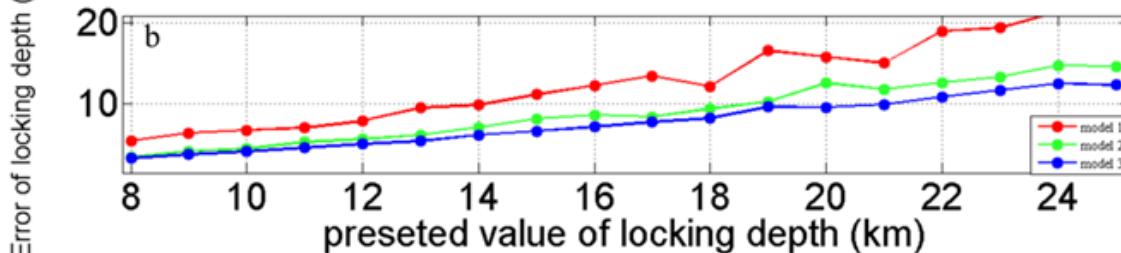
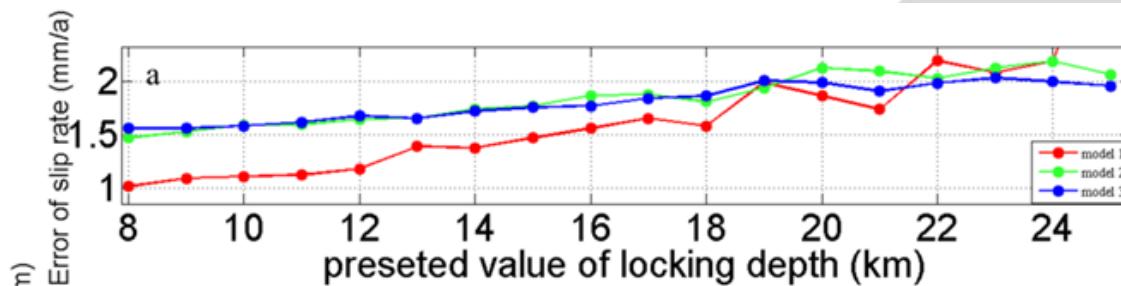
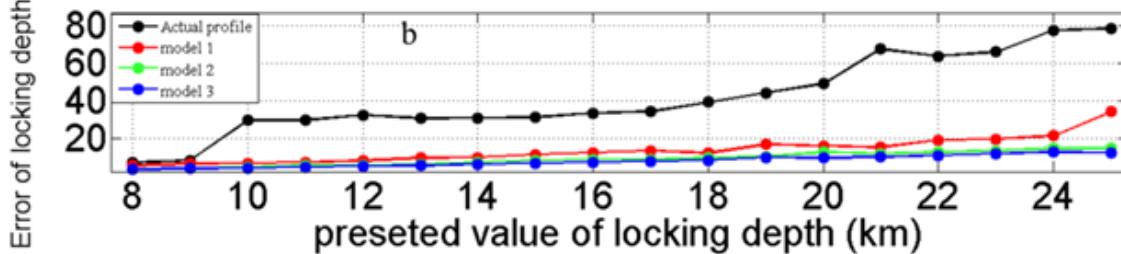
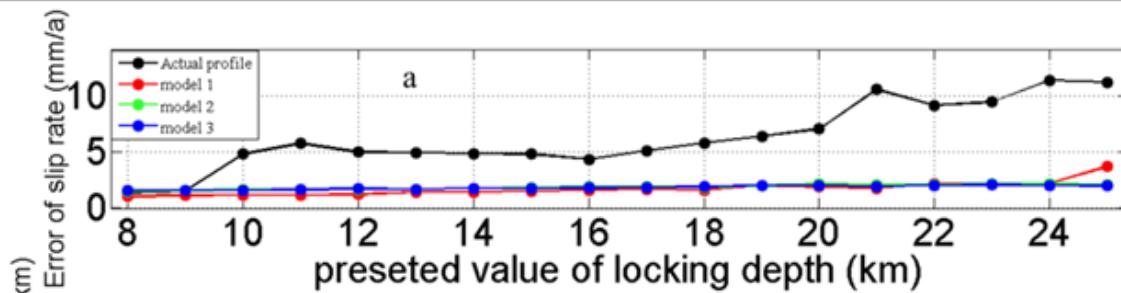
profile of the Qiaojia-Dongchuan segment of the Xiaojiang fault zone



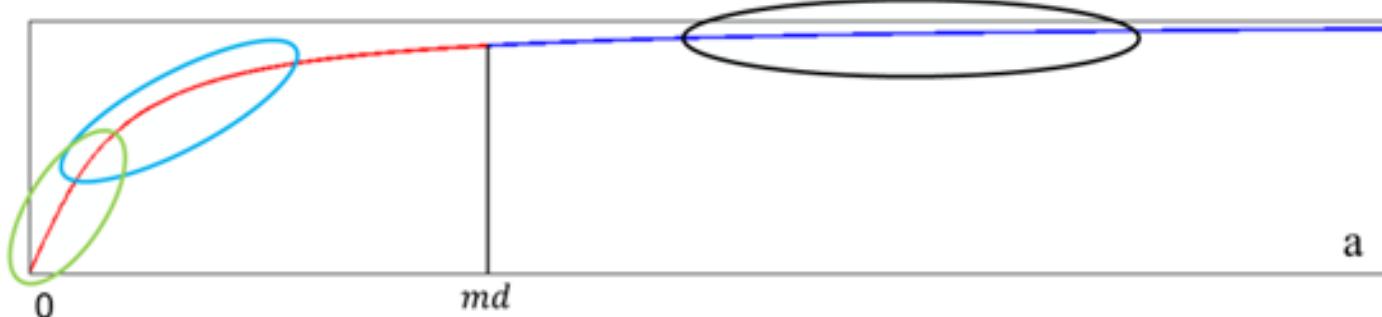
2011-2013年速度场，小江断裂带的巧家-东川段剖面

断裂带	站点数目	s (mm/a)	d (km)	s 的误差水平 (mm/a)
小江断裂带巧家-东川段	12	10	8~25	1



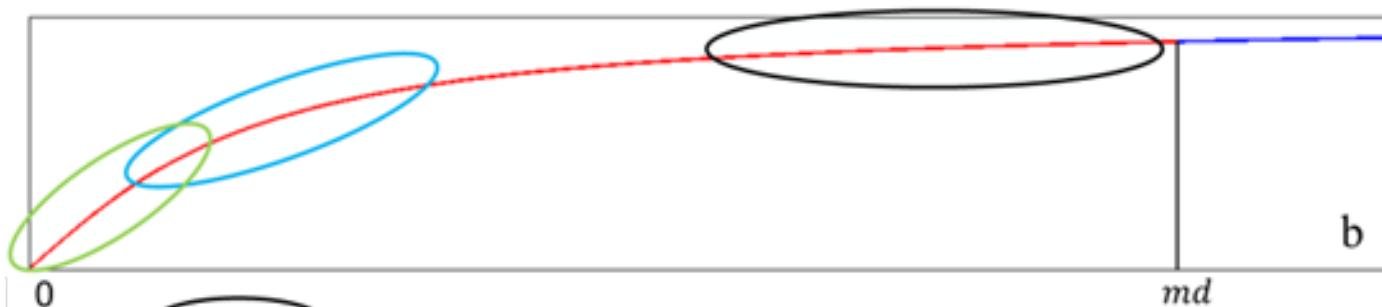


shallow locking depth deformation curve



a

deep locking depth deformation curve



b



densely layout area for model 1



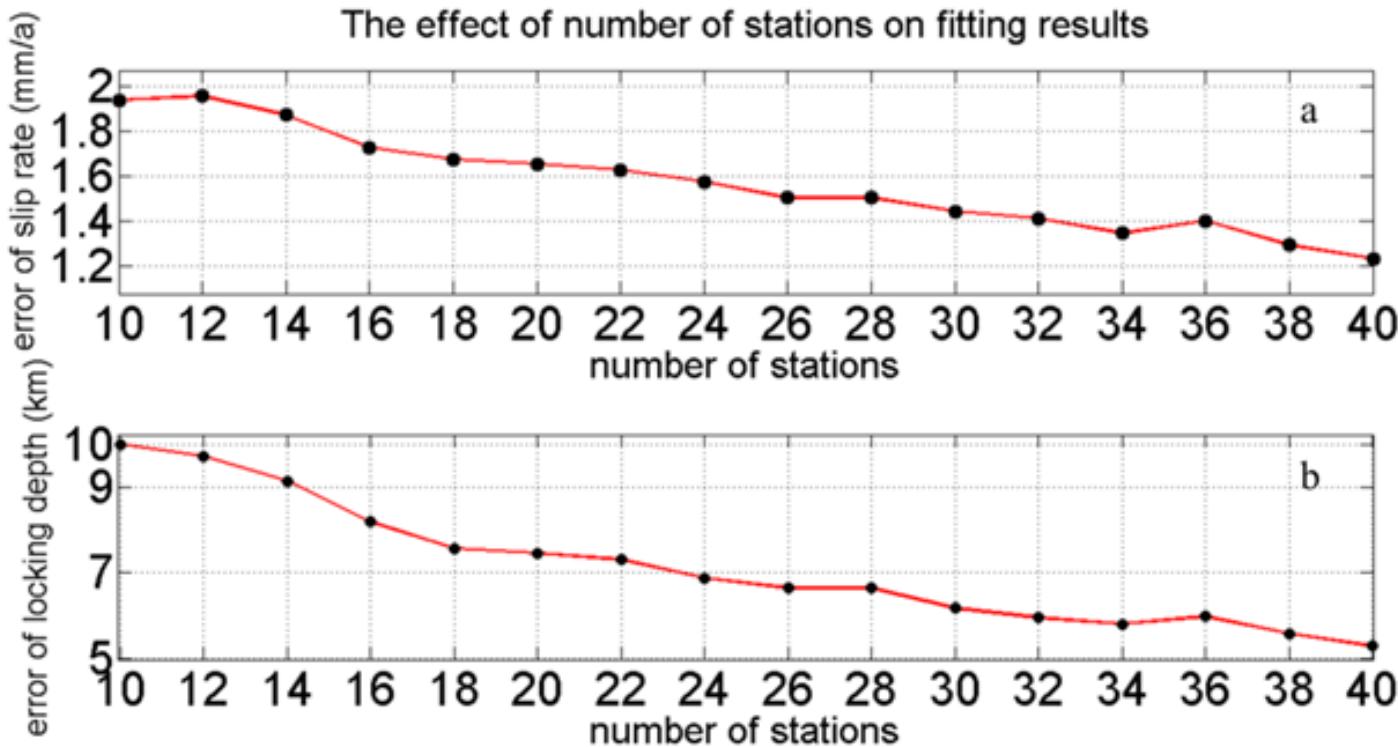
densely layout area for model 2



densely layout area for model 3

$$m = \tan\left(\frac{9\pi}{20}\right)$$

The effect of number of stations on fitting results



站名数目对结果的影响



主要结论：

- ①以形变量占总形变量的90%处作为有效距离。
- ②针对站点的间隔提出三种布设的模式，分别为等间距布设、等形变量布设和等斜率变化布设。
- ③布设模式得到的结果明显优于实际站点分布得到的结果。
- ④闭锁深度中误差计算结果表明模式3最优，其次是模式2，模式1最差。
- ⑤闭锁深度较浅时，模式1的滑动速率结果略优于模式2和模式3，但三种模式得到的滑动速率中误差对于 10mm/a 的断层滑动速率而言都是可接受的。在滑动速率结果可接受的情况下，建议选择模式3进行布设。
- ⑥站点数目的增加可明显改善结果精度。



到底怎么布设?

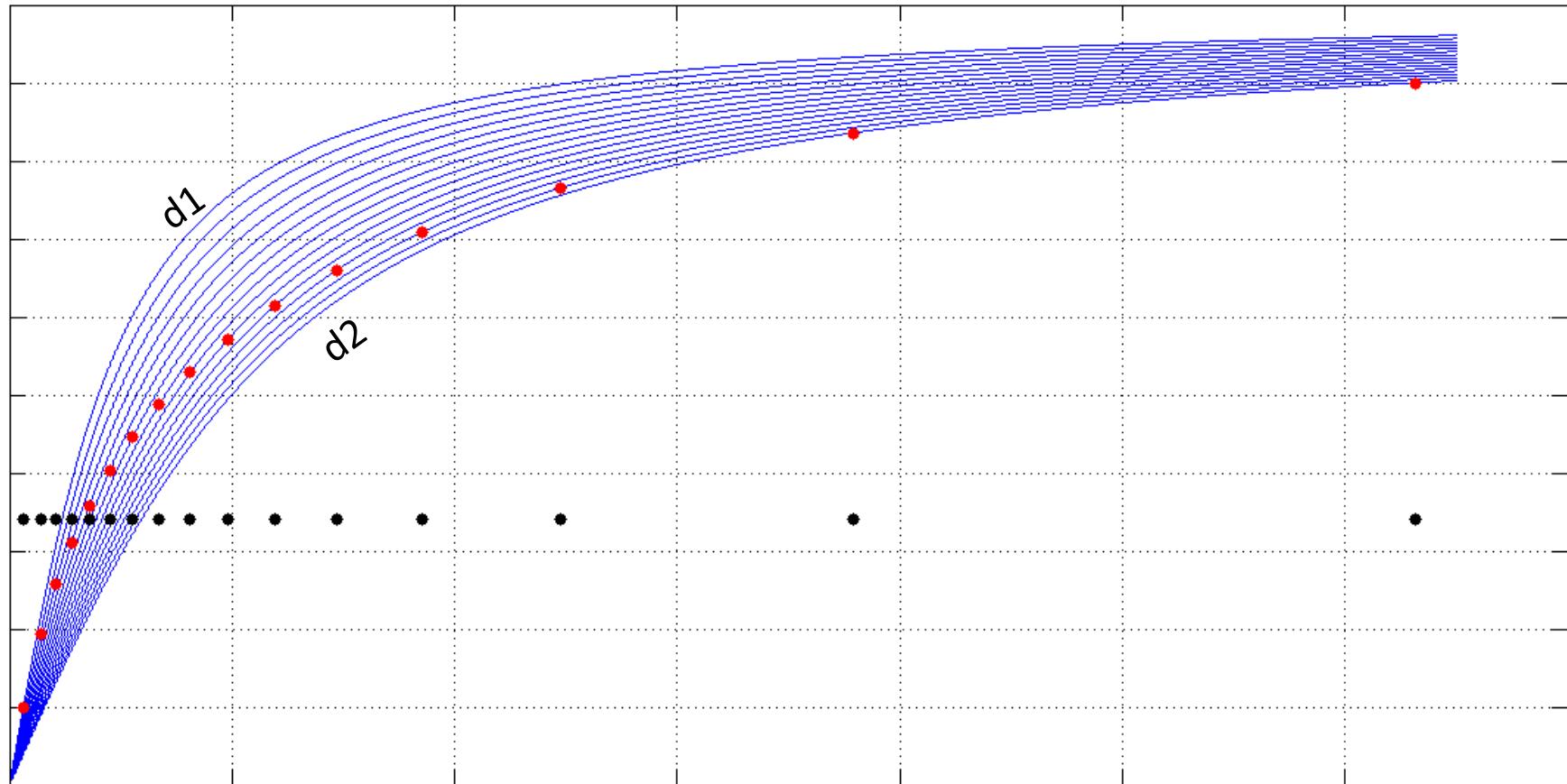
定位——在现有资料基础上加密过程，为了进一步得到更精确的闭锁深度和滑动速率

方案不唯一，更具上述得到的认识选择符合实际的方案

了解断裂带（段）闭锁深度的大致范围

根据需求，也考虑经费等现实能力

模式3，闭锁深度范围(d_1, d_2)



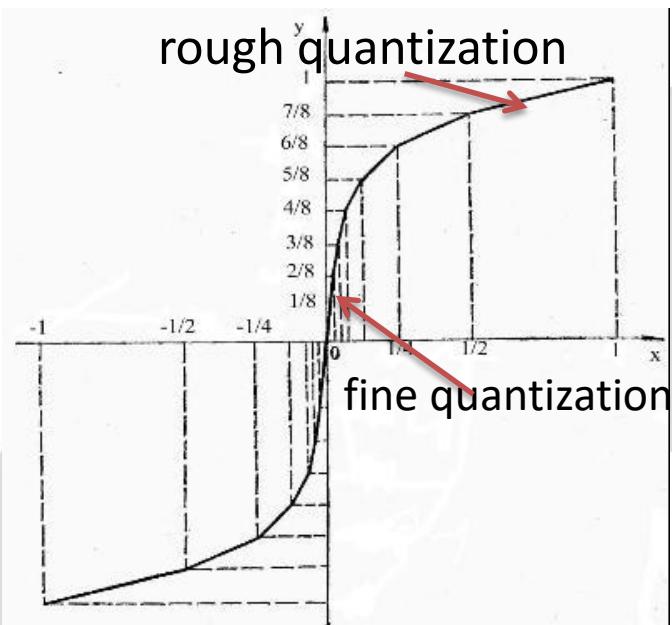
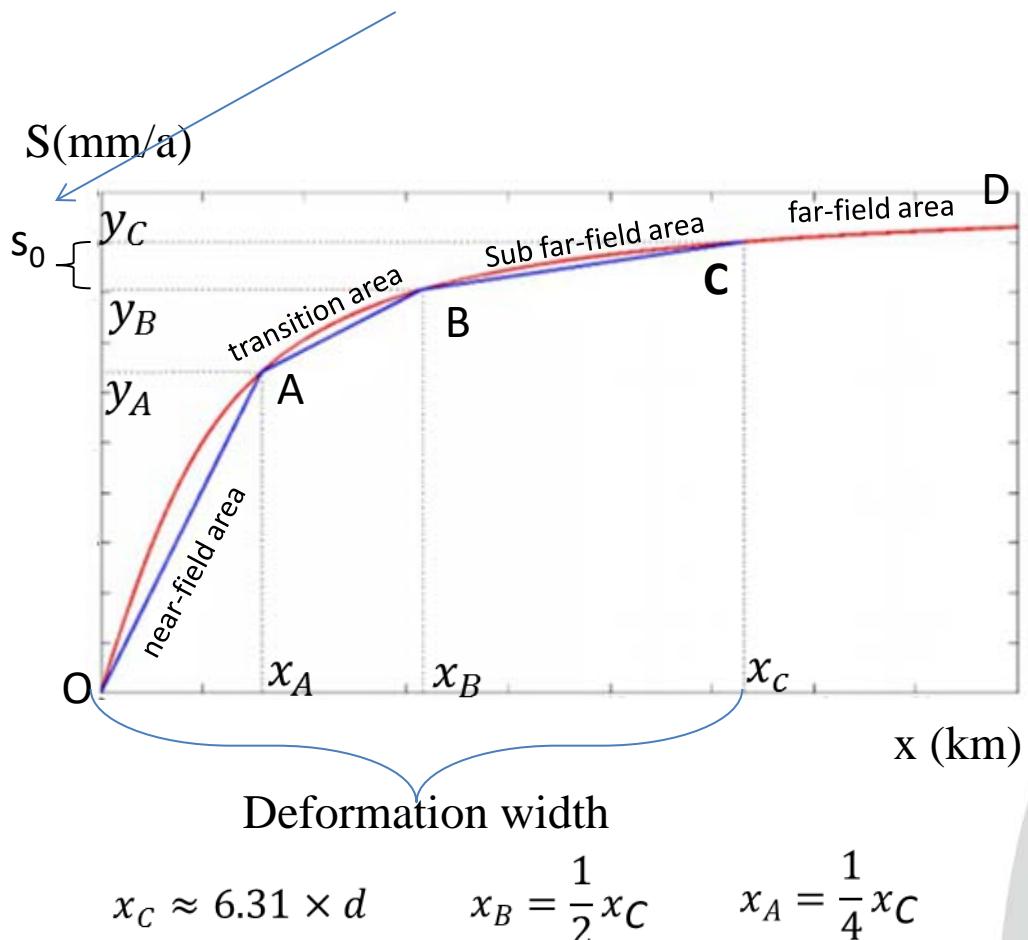


谢谢

请批评指正

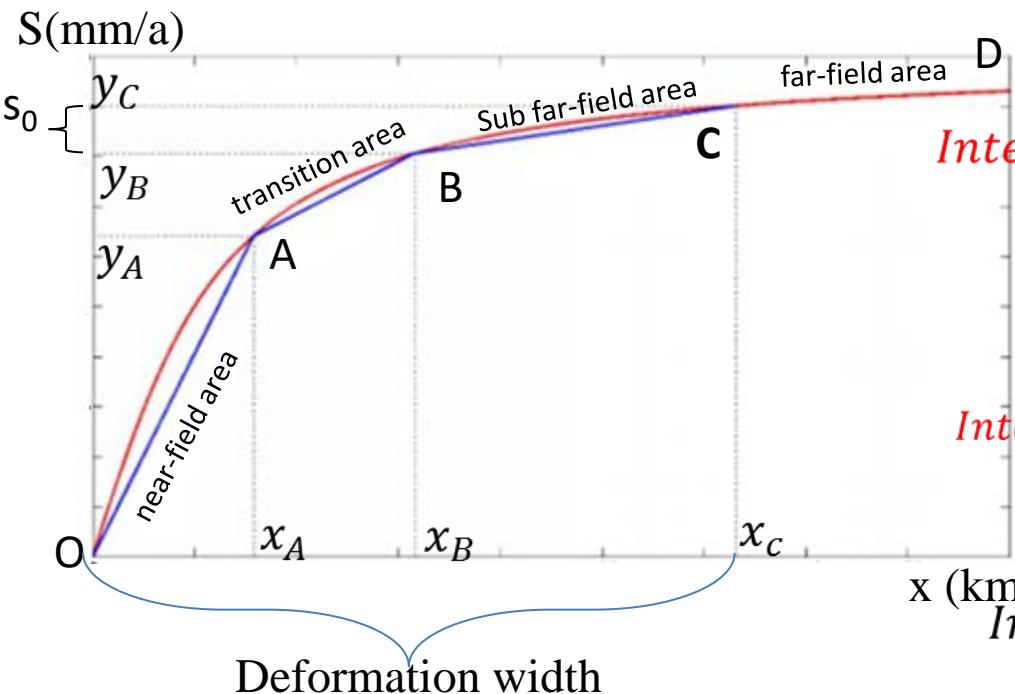
(2) 针对model2的初步方案

如何做出合理的纵向等分



A-law 13-fold line in the communication system

Horizontal and vertical coordinates of A, B, C:



$$x_A = \frac{md}{4}, x_B = \frac{md}{2}, x_C = md$$

$$y_A = \frac{s}{\pi} \cdot \tan^{-1}\left(\frac{m}{4}\right), y_B = \frac{s}{\pi} \cdot \tan^{-1}\left(\frac{m}{2}\right), y_C = \frac{s}{\pi} \cdot \tan^{-1}(m)$$

$$m = \tan\left(\frac{9\pi}{20}\right) \approx 6.31$$

Interval_{near} is interval of the near-field

$$\text{Interval}_{\text{tran}} = \frac{\tan^{-1}(m) - \tan^{-1}\left(\frac{m}{2}\right)}{4 \cdot \left(\tan^{-1}\left(\frac{m}{2}\right) - \tan^{-1}\left(\frac{m}{4}\right)\right)} \cdot m \cdot d$$

Interval_{tran} is interval of the transition-field

Interval is only related
to depth(d), not related
to slip rate(S)

verification

The locking depth of the San Andreas fault is 8.7 km (Smith-konter et al., 2010)

Range: $x_c \approx 6.31 \times d = 54.9 \text{ km}$ >50 km

Interval: $\text{Interval}_{near} = \frac{\tan^{-1}(m) - \tan^{-1}\left(\frac{m}{2}\right)}{4 \cdot \tan^{-1}\left(\frac{m}{4}\right)} \cdot m \cdot d = 2.04 \text{ km}$

$$\text{Interval}_{tran} = \frac{\tan^{-1}(m) - \tan^{-1}\left(\frac{m}{2}\right)}{4 \cdot \left(\tan^{-1}\left(\frac{m}{2}\right) - \tan^{-1}\left(\frac{m}{4}\right)\right)} \cdot m \cdot d = 7.96 \text{ km}$$

<6 km

and the locking depth D . An accurate estimate of the far-field velocity requires GPS velocity data more than several locking depths away from the fault (>50 km), while an accurate estimate of the locking depth requires a high density of GPS velocity data within one-half locking depth of the fault (<6 km spacing).

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, B06401, doi:10.1029/2010JB008117, 2011

Locking depths estimated from geodesy and seismology along the San Andreas Fault System: Implications for seismic moment release

Bridget R. Smith-Konter,¹ David T. Sandwell,² and Peter Shearer²

number

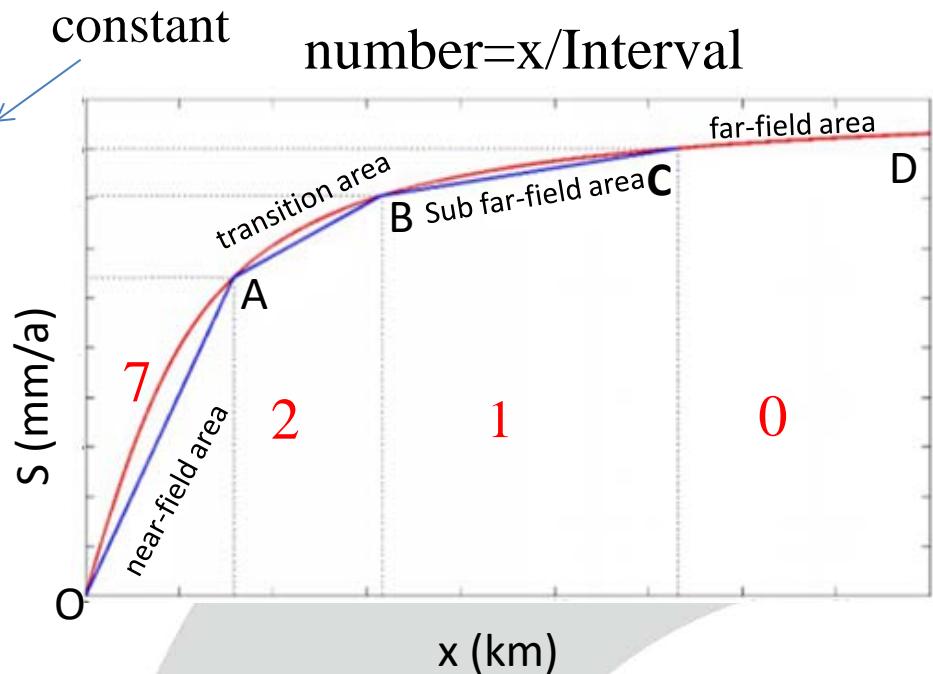
The number of GPS stations in near-field area

$$\left[\frac{\frac{1}{4}md}{l_n} \right] = \left[\frac{\tan^{-1}\left(\frac{m}{4}\right)}{\tan^{-1}(m) - \tan^{-1}\left(\frac{m}{2}\right)} \right] = 7$$

The number of GPS stations in transition area

$$\left[\frac{\frac{1}{4}md}{l_t} \right] = \left[\frac{\tan^{-1}\left(\frac{m}{2}\right) - \tan^{-1}\left(\frac{m}{4}\right)}{\tan^{-1}(m) - \tan^{-1}\left(\frac{m}{2}\right)} \right] = 2$$

$$y = \frac{s}{\pi} \cdot \tan^{-1}\left(\frac{x}{d}\right)$$



- The number of GPS stations is neither related to slip rate(s) nor locking depth(d).
- It only depend on the division model.

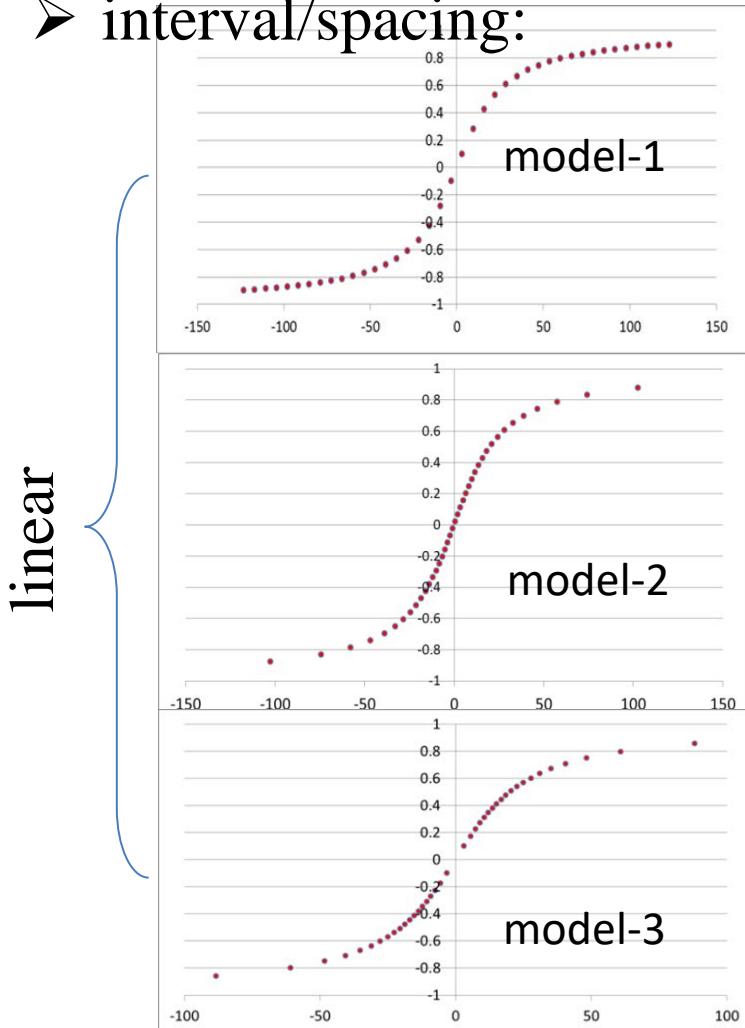
Results and discussion

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➤ Range: $6.31 \times d$

➤ interval/spacing:



$$x = k$$

$$\begin{aligned}x &= k \\k &= 0, 1, 2 \dots n - 1\end{aligned}$$

$$y = \frac{s}{\pi} \cdot \tan^{-1} \left(\frac{x}{d} \right)$$

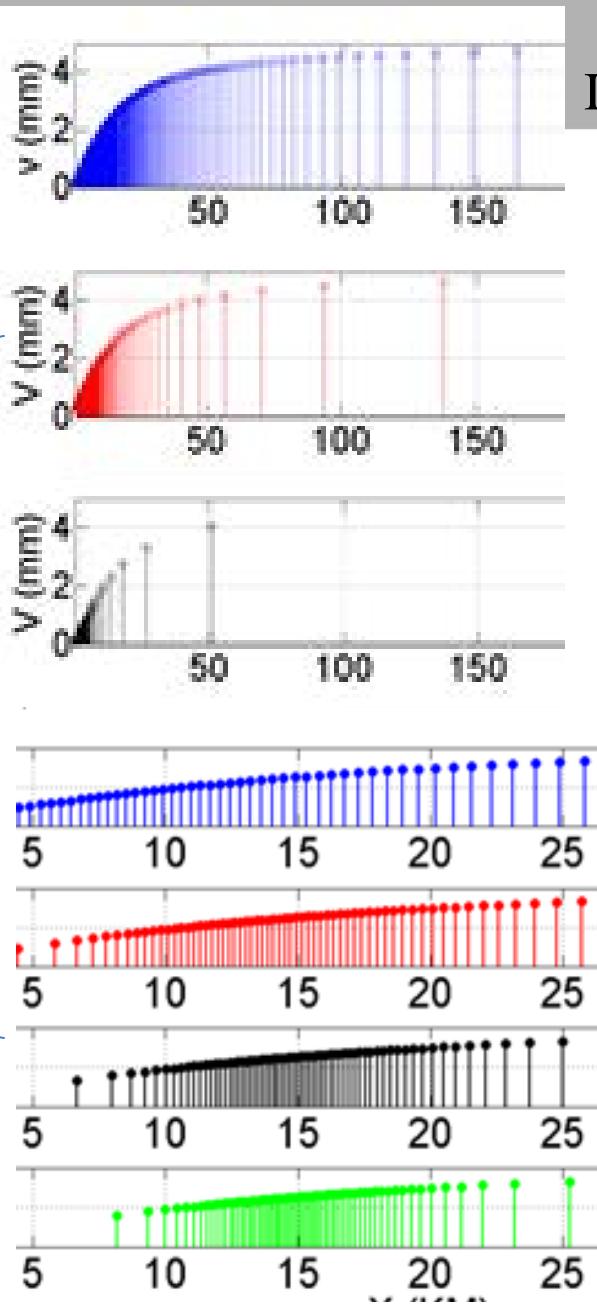
$$\begin{aligned}x &= d \cdot \tan \left(\frac{k\pi}{n} \right) \\k &= 0, 1, 2 \dots n - 1\end{aligned}$$

$$y = \frac{s}{\pi d} \cdot \frac{1}{1 + \frac{x^2}{d^2}}$$

$$\begin{aligned}x &= d \cdot \sqrt{\frac{n - k}{k}} \\k &= 1, 2 \dots n\end{aligned}$$

Improved model2

Non-linear



$$x = f^{-1}(y) \cdot (g'(y))^t$$

$$x = \frac{1}{d^{t-1}} \cdot \tan\left(\frac{k\pi}{n}\right) \cdot \left(\frac{1}{1 + \frac{k^2}{n^2 \cdot d^2}} \right)^t$$

$$k = 0, 1, 2 \dots n - 1$$

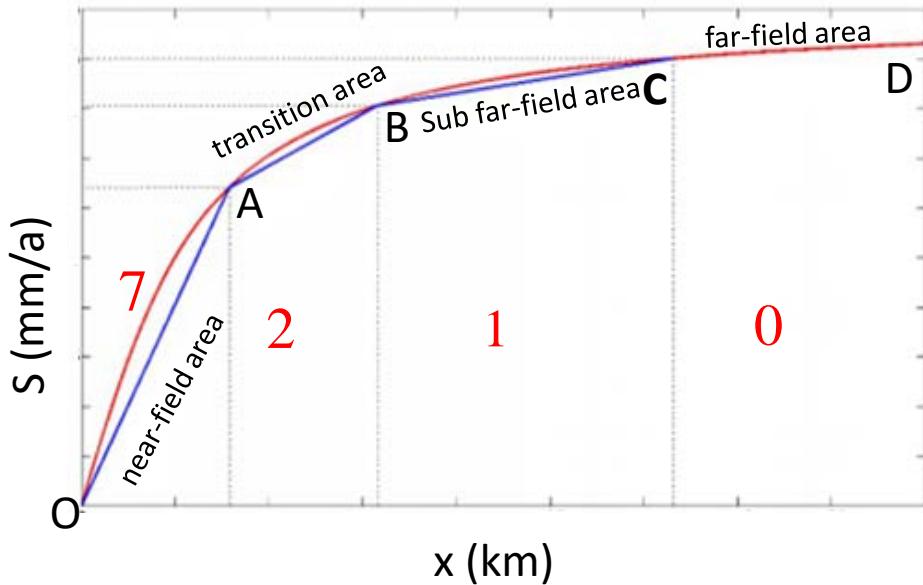
$$y = \frac{s}{\pi d} \cdot \frac{1}{1 + \left(\frac{x^2}{d^2}\right)^t}$$

$$x = d \cdot \left(\frac{n-k}{k}\right)^{\frac{1}{2t}}$$

$$k = 1, 2 \dots n$$

Improved model3

- 针对模型2给出一个初步的布设方案



布设的**站点数目**与**滑动速率**无关，
也与**闭锁深度**无关。仅与各区域
划分方式有关。

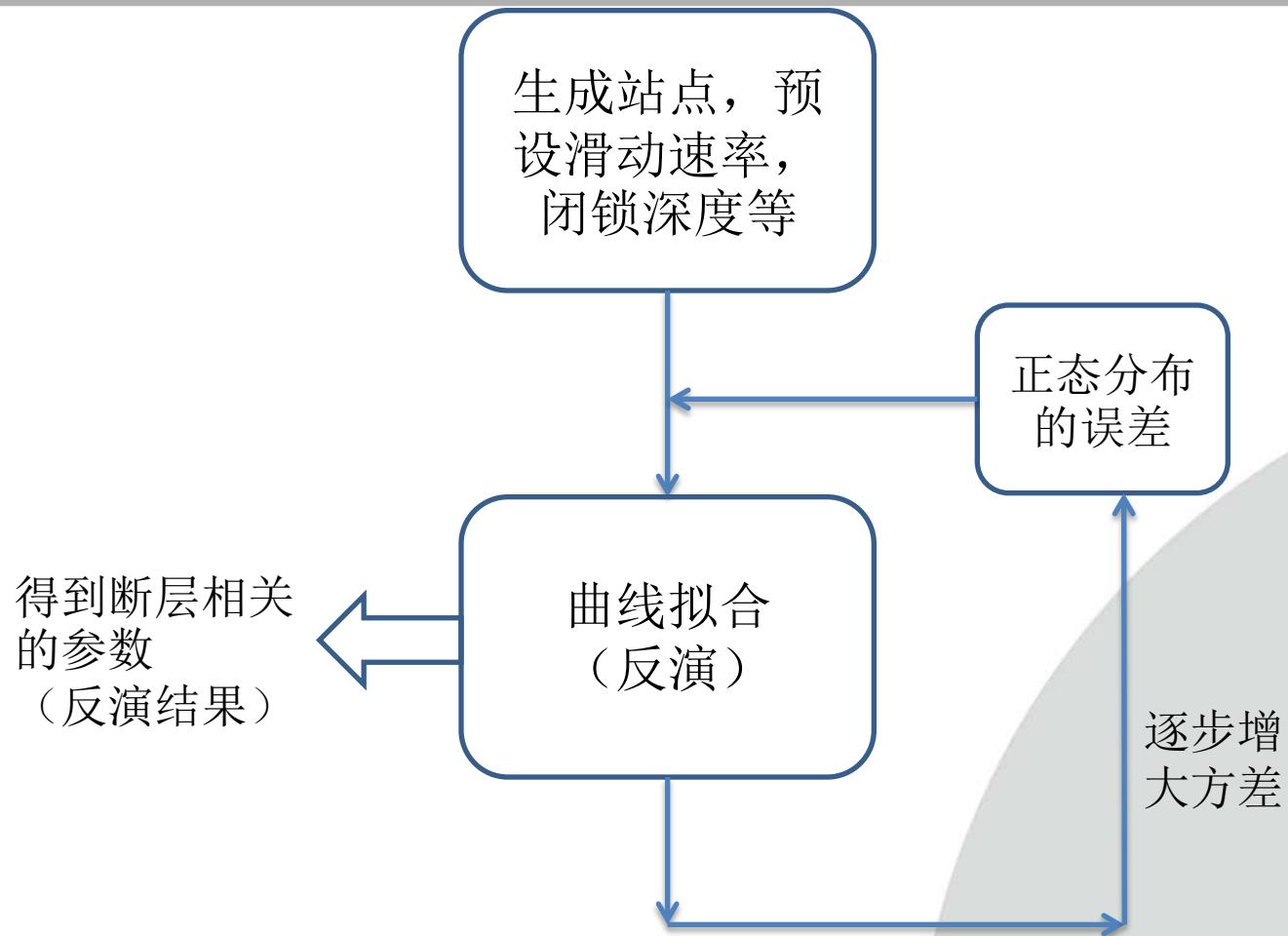


Thank you!

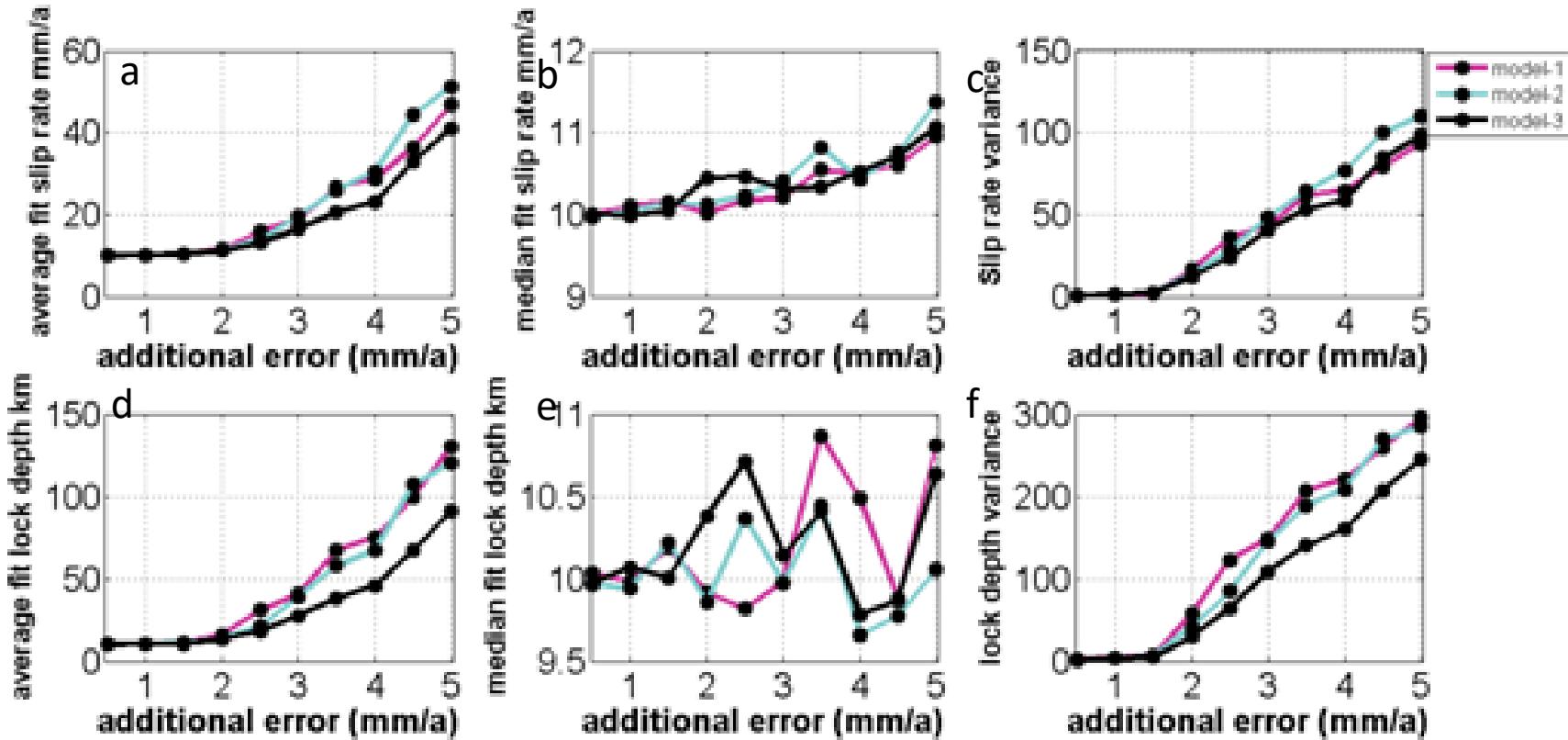
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- Rational layout of GPS stations
- The relationship between fit parameters precision and site layout, Observation accuracy and sites number



一定的滑动速率下，速度场误差水平对结果的影响

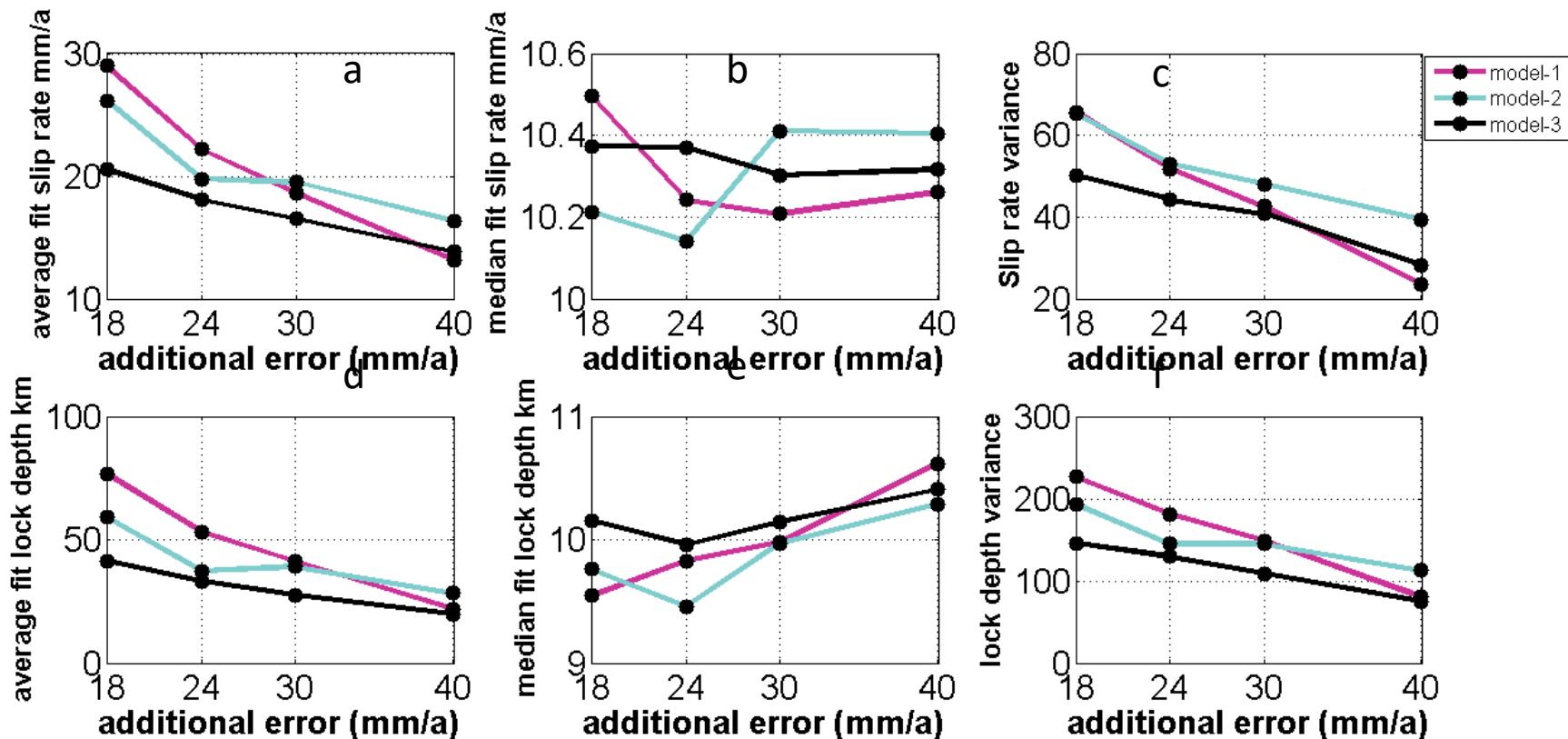


误差水平对结果的影响

滑动速率10mm/a, 闭锁深度10km, 30个站点

a 滑动速率平均值; b 滑动速率的中位值; c 滑动速率中误差
d 闭锁深度平均值; e 闭锁深度的中位值; f 闭锁深度中误差

站点数目对结果的影响

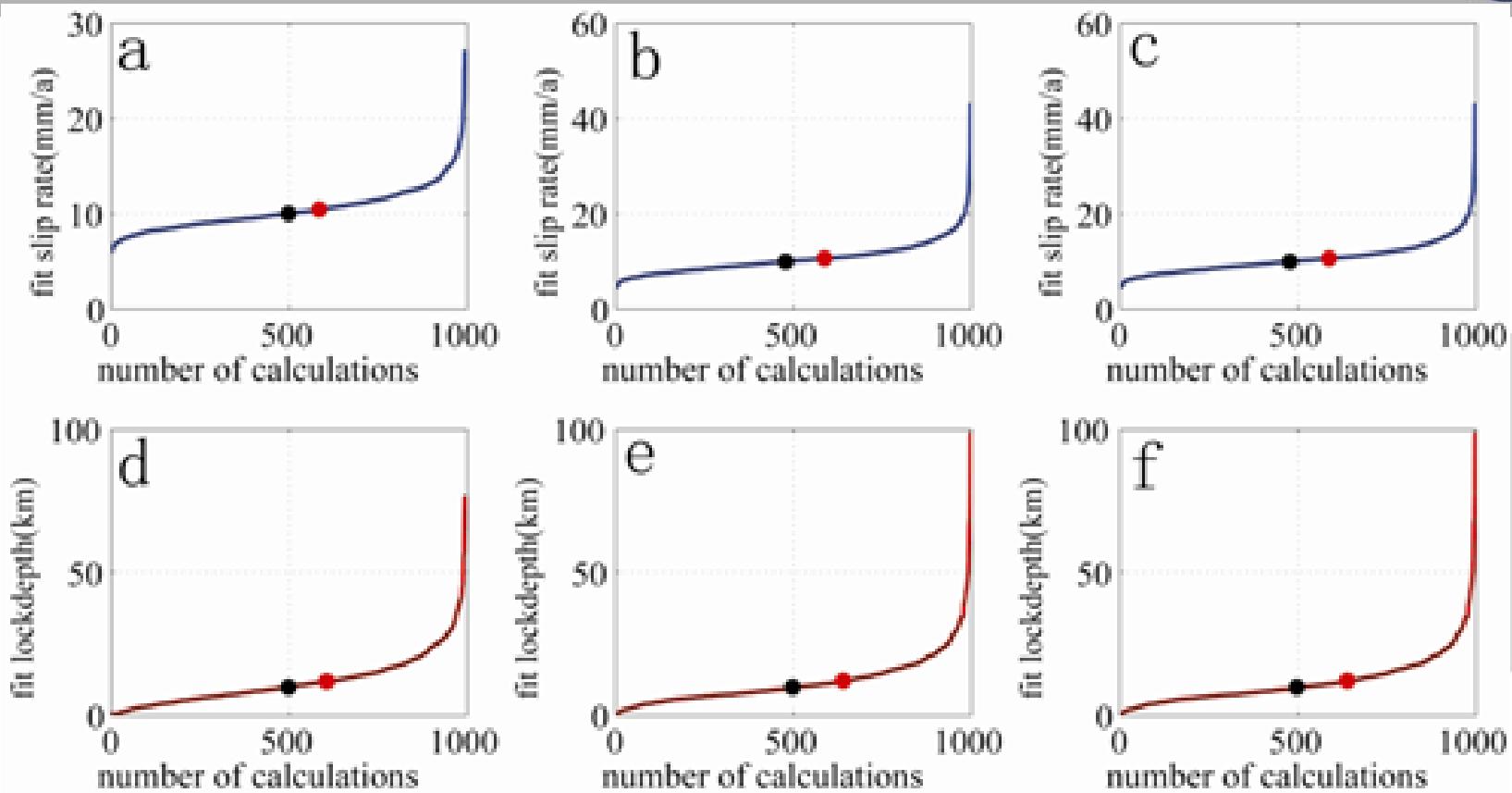


站点数目对结果的影响

滑动速率10mm/a, 闭锁深度10km, 误差水平3mm/a

- a 滑动速率平均值; b 滑动速率的中位值; c 滑动速率中误差
- d 闭锁深度平均值; e 闭锁深度的中位值; f 闭锁深度中误差

中位值与平均值的比较



拟合结果取平均值与中位数比较

滑动速率10mm/a, 闭锁深度10km, 30个站点, 误差水平2mm/a

a 滑动速率, 模式1; b 滑动速率, 模式2; c 滑动速率, 模式3

d 闭锁深度, 模式1; e 闭锁深度, 模式2; f 闭锁深度, 模式3

黑点为中位数结果, 红点表示平均值结果

实际布设时，断层的闭锁深度未知

以现有的闭锁深度结果作为参考值，布设密集站点做精细化的形变监测。

针对闭锁深度在 $d_1 \sim d_2$ 之间，目前初步考虑两种布设思路（合理与否需讨论）：

1、从地震危险的角度，对于中国大陆地区，如果 $d_1 < 7\text{KM}$, 说明断层闭锁深度即便为 d_1 ，应变积累能量有限

即：以 d_2 为闭锁深度参考值布设站点，用以监测断层可能发生较大地震的形变。

2、近场区以 d_1 布设，过渡区以 d_i 布设, ($d_1 < d_i < d_2$)，远场区以 d_2 布设

第一种思路需站点数目较少，但断层近场形变的精细变化可能监测不足；第二种思路可完整近，中，远场的监测，但所需站点较多



Thank you!

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Next work